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JUN 81 J A SMITH, M J GOODWIN, M S MCBRIDE
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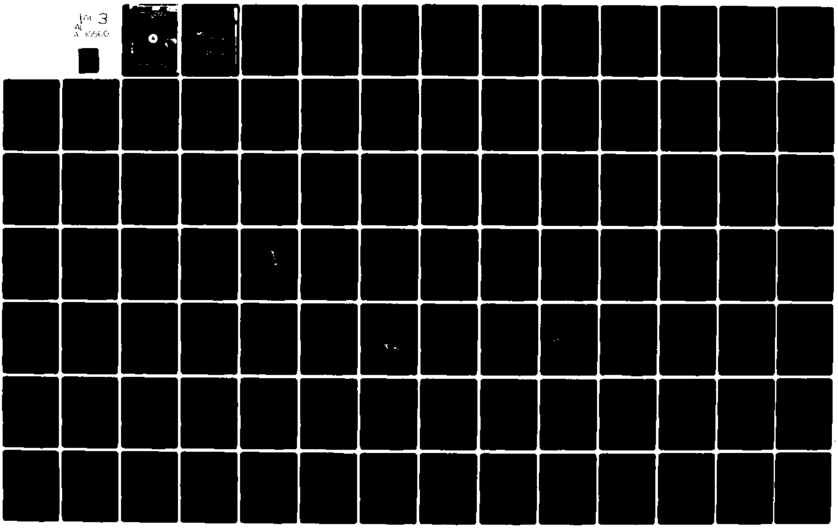

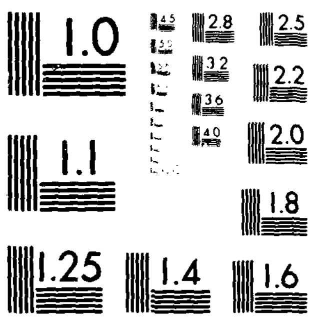

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16. Abstract

This report represents the first comprehensive evaluation and ranking of all the auxiliary icebreaking devices which have been proposed over the last fifty years. An extensive literature search and interviews with experienced Coast Guard personnel produced a list of 19 alternatives to evaluate. Decision Analysis was used to rank order the alternatives based on their utility in meeting the goals and objectives of the Coast Guard. One system was clearly superior than the others. This was the Pitching System in which a set of rotating weights are used to induced a pitching motion to the hull while icebreaking.

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METRIC CONVERSION FACTORS

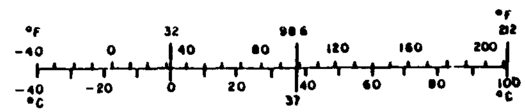
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



VOLUME 1

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1.0 INTRODUCTION

1.1 Scope

This report catalogs and ranks proposed auxiliary icebreaking devices/systems suitable for use in the Great Lakes. The purpose of this report is to describe the analysis for comparing such devices as: Pitching Systems, Air Bubblers, Mechanical Saws, Icecutters, Lasers, etc.

Since a large quantity of information had to be considered in order to provide a valid ranking, a Value Model was developed to evaluate the expected performance characteristics of the icebreaker/auxiliary device system as well as the uncertainties in those characteristics, the relative importance of each of the attributes of the devices, and the effects of varying operating conditions. The basic elements of this model include identification of the decision makers (icebreaker operators, administrators, and engineers), the existing conditions (ice and weather), the decision parameters (attributes of the proposed devices), and the possible outcomes associated with the alternatives.

The analysis focused on the auxiliary system's ability to improve the performance of the host vessel. It produced a set of weighted matrices for each alternative device transforming the multi-dimensional problem into a single figure of merit based on the best available information obtained from literature searches and operators. The end-product of the analysis is a ranked list of auxiliary devices showing which devices are most effective in the icebreaking mission and deserve further study.

1.2 Background

A need has been identified by managers of the U.S. Coast Guard Icebreaking Programs to improve the performance and effectiveness of the icebreaking fleet. One approach to meeting this requirement is to develop auxiliary icebreaking devices which will, either actively or passively, improve the hull-ice interaction of conventional icebreakers.

The hull-ice interaction can be improved in several ways including, among others, improved breaking or weakening of the ice, displacement of broken ice from the channel, or reduction of hull friction. Numerous feasibility studies, model tests, and full-scale evaluations performed during the late 1960's and 1970's have identified many devices and concepts which can be applied in conjunction with conventional icebreakers to improve overall performance and effectiveness. These devices are materials, accessories, or apparatus which may be built into a ship, installed or attached to the ship seasonally, or installed on a mission basis.

The initial phase of this project was a planning work effort. The objective of that effort was to review existing project plans and to generate a work statement that can be used by the Coast Guard to conduct a multi-phase R&D program with (1) a data-gathering effort including collection of existing data, model testing, and data analysis; (2) detailed development of a working methodology that can be used to analyze and select feasible auxiliary devices/systems; and (3) a model and full-scale development program of feasible devices/systems.

The work statement expressed the need for a rational scheme for evaluating auxiliary devices. A methodology was proposed which uses decision analysis to identify the "best" of competing auxiliary devices/systems strategies for icebreakers. The decision-making methodologies presented ranged from simple to complex. The work statement was very helpful in pointing out the steps that need to be taken to model the "decision" process. The foregoing activities led to the formulation of the Value or Decision Model.

1.3 Summary of Results

The first task necessitated gathering as much information as possible about icebreaking apparatus and methods in order to develop a list of alternative auxiliary icebreaking devices. The effort was then directed towards systematically searching the list for the devices which most likely deserved further study and/or development. An extensive literature search, (see references), and many interviews with experienced operational personnel produced a list of 19 alternatives to evaluate.

Operational experience and engineering judgement were considered to be the most important factors in providing quantitative information to be used in ranking the list of devices. Day-to-day activities aboard the icebreaker would be directly affected by the installation of an auxiliary device. If one could extract information concerning how these activities would either be adversely affected or positively reinforced by a particular device and quantify that information, then the devices could be ranked accordingly. Selection would then be based on the auxiliary device which would most likely produce improved ice operations if installed on an icebreaker.

The activities were described by a set of parameters or attributes. The attributes were especially selected so that an operator would be able to relate his icebreaking experiences to a wide range of numerical values of the attribute while operating in a particular mission environment, e.g., speed in a certain type of ice while channel clearing. The operator provided us with his preferences for specific values of the attributes thereby indicating how he would "like" the device to operate. The engineer provided us with estimates of how a particular device would most likely "perform" in a particular mission environment. The Decision Model essentially combined these two kinds of information and produced a ranking of the auxiliary devices for each of the 13 operators interviewed.

The analysis, for ten out of the 13 operators, selected the device called a "Pitching System" as the one which would most likely improve day-to-day ice operations if installed on an icebreaker. Since costs were not analyzed it should be noted that an estimate of 1 million dollars per installation of the pitching system is not considered to be unreasonable. Future studies must be undertaken to determine if the increase in performance outweighs the cost to implement this device.

2.0 METHOD OF APPROACH

2.1 The Alternatives

The following set of devices were selected for the comparative analysis:

- Lasers
- Pitching Systems
- Mechanical Icecutting
- Explosive Icebreaking
- Hydroflushing Equipment
- Air Cushion Vehicles
- Water Jets
- Upper Mississippi Icebreaker
- Alexbow Barge
- Bubbler Systems
- Mechanical Saws
- Archimedes Screw Vehicle
- Mechanical Impact Device
- Water Hull Lubrication Systems
- Low Friction Hull Coatings
- Stem Knives
- Bow Ramp

A harbor tug with icebreaking capability, 140' WTGB, was used as the "base line" alternative, i.e., all the devices were measured relative to the 140' WTGB with no devices. Some devices, such as the "Laser" alternative, had not been tested and were mere conceptual designs at the time of this writing. Others, such as the "Bubbler System," have been incorporated into the new 140' WTGB icebreakers recently commissioned to operate on the Great Lakes. The varying amounts of test data for the devices and the fact that few have been tested on board an existing Great Lakes Icebreaker, made the comparative analysis more difficult.

Sketches of the devices can be found in Appendix A. These are an artist's conceptions of feasible ways in which the devices could be retrofitted to a 140' WTGB. Other configurations certainly could be designed for many of the devices.

2.1.1 Description of Alternatives

Laser (Figure A-1)

Feasibility of Laser-assisted ice breaking is due to the fact that relatively little power should be required to initiate cracks or to assist crack propagation for use with conventional icebreaking techniques. Since ice is weak under tension, laser beams would strike the ice adjacent to the bow of the ship on both sides where the ice is under tension. Pulsed lasers that can deliver much higher peak powers may work more effectively by, in essence, perforating the ice. The pressure pulse from explosive steam formation could also greatly enhance the cracking.

One possible design using a 50W laser with a beam of 10.6 μm wavelength and about 1 cm^2 cross section using a 62-cm focal length

mirror was used for focusing the beam with a resulting power density of about 500 W/cm^2. Experiments were performed (Coburn) using a CO_2-TEA laser with an energy of 1/2 Joules and a pulse width of 1 μsec focused with a 30-cm lens.

A figure of merit for ice cutting is the area of the cut (depth times length) per unit time for a given laser power. For assisting ice breaking the width of the cut is not as important and is directly related to the laser focusing optics. For the above experiments, this number would be 8 cm^2/(sec x kW). Translated into meaningful terms for ice breaking, these figures indicate 50-100 kW would be necessary to make an 8-cm deep cut in ice at the rate of 1 knot. Lasers of this power are feasible, could be accommodated on board ships, and their cutting ability could enhance present ice breaking abilities.

Successful application of lasers to ice breaking requires not only optimization of the laser power transfer to the ice but a better understanding of the fracture properties of ice. Present knowledge in this area is quite limited (Weeks). The critical stress in density factors for a sharp crack, as well as a laser cut, in both lakes and sea ice should be determined. Stress and fracture analyses of the ice surrounding a ship should be done for various thicknesses and temperatures to determine the optimum location of a laser cut for crack enhancement. The effects of much higher power pulsed lasers should also be pursued, especially in colder ice and at wavelengths other than 10.6μm which is totally absorbed near the surface. The explosive formation of steam by an energy pulse focused beneath the surface of the ice could be very effective for crack generations. Since the absorption coefficient of ice for 1-μm radiation is 3 orders of magnitude less than that for 10.6 μm, a high power pulsed neodymium-glass or neodymium-VAG laser operating at 1.06 μm should be capable of achieving this effect. Although accurate values for the absorption coefficient of ice for $\lambda < 0.95 < \mu$m are not available, even higher transmission at these wavelengths may be inferred from the behavior of the absorption coefficient of water. Scattering from the inclusions, defects, and bubbles present in lake and sea ice will decrease the transmission, although the magnitude of this effect is unknown. Use of a laser operating in the visible portion of the spectrum would allow the possibility of generating cracks from underneath the ice immediately in front of the ship.

<u>Pitching System</u> (Figure A-2)

Several icebreakers have been fitted with equipment to produce pitching and rolling motion in order to reduce the danger of becoming ice bound. This equipment shifts moments about the longitudinal or transverse axis with sufficient rapidity to attain something of the ship's natural rhythm of pitch or roll.

In a particular arrangement, two weights located in the forward quarter contrarotate on the same axis; the resultant forces neutralize each other on the horizontal plane and become additive in the vertical plane.

In 1953, the Federal Republic of Germany and other countries announced several patents suggesting that icebreaking should be accomplished by a "dynamic" rather than the conventional "static" force exerted by the ship's bow (Grim). The dynamic loading of the ice cover can be produced as a

result of oscillatory motion of the ship about a transverse axis. The ship vibration relative to the water is caused by an onboard excitation unit.

The patents suggest several alternative types of the excitation units. One alternative consists of two eccentric masses which rotate in opposite direction about a transverse horizontal axis with the same angular speed. In this case, the horizontal components of the centrifugal forces produced by the rotating masses will cancel, whereas the vertical components will be superimposed and added in the vertical plane. In another alternative, there is only one mass and the hull moves also in the longitudinal direction (forwards and backwards). In yet another alternative, the excitation unit consists of two rotating masses which are respectively located in the bow and aft section of the ship and attached to the ends of a longitudinal shaft in locations which are 180^{0} apart. Finally, another alternative design is a longitudinal U-shaped pipe located in the plane of symmetry of the ship. The pipe is filled with a fluid which is brought into oscillatory motion by a propeller pump with adjustable blades which is located in the bottom part of the pipe. The oscillation of the fluid then leads to oscillatory motion of the ship. (This is called a pneumatically induced pitching system, PIPS).

One of the most important requirements on the excitation unit is that of continuous regulation of the angular velocity of the rotating parts. Variable vibration frequencies of the hull can then be attained. From the viewpoint of icebreaking, the most effective frequency of the excitation unit should be in the vicinity of the natural frequency of the ship. The actual value will be influenced by the thickness and quality of the ice cover. The continuous regulation of the excitation unit can be accomplished by mechanical, hydraulic, or electrical devices.

<u>Mechanical Icecutting</u> (Figure A-3)

There are a multitude of tasks that involve the cutting of natural ground materials such as ice. The required technology varies with the properties of the materials and with the scale of operations. In strong materials that exhibit brittle fracture characteristics (e.g. rock, concrete, ice, frozen ground) the forces and energy levels required for cutting and breaking are quite high.

When icebreakers make their way through thick ice sheets, high propulsive outputs are required. Many designs using ice cutting techniques have been proposed to improve upon the efficiency of the propulsive output by ship-mounted booms carrying tools for cutting grooves into the ice sheets so that the ice may be broken more easily or even broken up entirely.

Typical of many of these designs is an icebreaker characterized by a cantilever above the ice projecting from the forecastle of the ship's hull. A plurality of planing tools are secured to the cantilever by means of a sliding carriage. The carriage is adapted to be lowered onto the surface of an ice sheet where it is coupled to a vibrating device for generating small amplitude high frequency vertical vibrations. The icebreaker may also be arranged in a manner allowing withdrawal of the sliding carriage when the icebreaker is travelling in open seas.

The USSR Design Office for Excavation of Ice, Snow, and Permafrost produced a light, self-propelled ice cutter with an electric engine. It had been constructed in a sled with electric power supplied by a cable. The cutting of the ice was accomplished by a tubular milling cutter with a built-in helical conveyor. During the cutting, the ice powder falls into the cutter through spherical openings and is subsequently pushed under the ice. The cutter made a 0.2m wide cut at the speed of 72 m/hr in 1/2 m thick ice. The energy consumption in the process is 0.55 H.P./m^3. The propulsion of both the sled and the working tool was provided by the same electric engine. The cutting machine weighed about 400 kg.

Another icecutting machine on rotating cylindrical screw propellers attained higher travel and working speeds due to larger engine output, longer and larger diameter propellers and more loops of the helical blades.

The travel speeds reached during testing were: 18 km/hr on ice with a snow cover; 12 km/hr in water. The work speeds were up to 400 m/hr, depending on the ice thickness, and the towing force was 3650 kgs (on ice with a snow cover).

Explosive Icebreaker (Figure A-4)

This technique was conceived at the Southwest Research Institute and is an extension of an earlier idea for an explosive earth-moving device. A combustion chamber is charged with a mixture of compressed air and hydrocarbon fuels. This mixture is exploded by a spark plug and the pressure within the chamber rises to a value six to eight times the initial charging pressure. Upon signal, one (or more) large exhaust valve(s) is driven open in about 25 msec by gas pressure and the hot, pressurized gas in the chamber is released.

A barge carrying a number of combustion chamber exhaust valve assemblers is pushed under the ice by a towboat or other means. The high-pressure exhaust gas is used to break the ice sheet. The ice fragments are deposited on the unbroken ice to the side of the channel.

A viable icebreaker configuration for continuous icebreaking duties would use the fuel air explosion to impact the ice sheet producing radial cracks. The weight of the icebreaker would be used to fracture the resulting ice beams. The discharge ports would be located in the ship's hull to relieve the stresses and frictional drag on the sides of the icebreaker bow, as well as to produce the necessary radial cracks.

These units would prove beneficial for maneuvering a vessel in both sheet and brash ice. For operations in sheet ice, the unit could be used to fracture ice on either side of a vessel thus providing clearance for turning the vessel. Low pressure discharges, which will not fracture hard ice, could be used to displace mush ice.

The design concept for an "explosive icebreaking" system was developed under a previous U.S. Coast Guard Contract (DOT-CG-02-815A). Analysis for this effort demonstrated a high degree of feasibility for the application of this technology to ice fracturing. These analyses, however,

were not sufficient to define the actual fracture characteritics of the ice nor the influence of ice strength on the possible modes of ice failure. An Explosive Icebreaker barge was tested under Contract DOT-CG-12118A in January 1973. This test concluded that the fuel/air explosives can be efficiently used for ice fracturing.

Hydroflushing Equipment (Figure A-5)

The principle underlying the action of this equipment is that intake water sucked in by pumps is discharged in the form of jets through nozzles located both in the underwater part of the hull of the vessel and through its bottom, into the region in which the ice fragments are concentrated. The jets repel the ice fragments from the sides and the bottom. This reduces to a considerable degree the total resistance of the crushed ice to the motion of the vessel. Thus, when the hydroflushing equipment is installed in an icebreaker, the increase of its capacity of riding through ice is obtained by a decrease of the friction of ice against the hull and of the expenditure of energy for pushing apart and turning over fragments of crushed ice.

Structurally, this equipment consists of high-performance pumps with a low outlet pressure, of piping, and of outlet nozzles. The water intake is effected through openings in the hull of the vessel which are located at positions of the least possible concentration of crushed ice -- at the bottom of the hull.

Laboratory tests have shown (Antonov) the capacity of riding through ice of a vessel provided with the hydroflushing equipment is increased by 15 to 20%. At the same time, a considerable cleansing of the channel of broken ice is obtained, the largest part of which is driven by the water jets from the nozzles under the undisturbed edges of the ice cover which form the "banks" of the channel.

Air Cushion Vehicle (ACV) Bow (Figure A-6)

Recent Canadian operational experience has shown that air cushion configurations possess a surprisingly large capability of breaking ice.

An air cushion craft may break an ice sheet by one of two methods:

a. The low speed method in which the cushion pressure develops an air pocket beneath the ice and causes the ice to fail under its own weight.

b. The high speed method in which the air cushion, moving across an ice sheet at the resonant speed of the ice sheet, causes the ice to break from the dynamic amplification of the vertical motion of the ice sheet.

The high speed method is much the more powerful of the two methods of icebreaking with air cushions. However, the ACV bow which is mounted at the bow of a displacement hull to break the ice must use the low speed method. The ice is then cleared by the pusher ship (air cushion configuratons break, but do not clear, an ice field).

Water Jets

Ice breaking by pulsed water guns (Sviditelstvo) which can generate pulsed jets at several thousands of atmospheres have been investigated and appear promising. Laboratory experiments have shown that a pulsed water gun, (IV-5), can break a large, (50 x 60 x 70 cm^3), block of ice into small pieces when the block is placed 4.5 m from the nozzle. Only one liter of water is used in the process.

In a field investigation on the Obsk reservoir at Novoskbirsk, Siberia, this water gun was used to make a passage in fast massive ice which remained in shore after water abatement. The size of the passage was 6.5 x 2.6 x 0.8 m^3; the gun fired 70 pulses of water. The rate of work of the gun was 347 m^3/hr at 30 pulses per minute. The cost of the icebreaking operation in this case was 17 cents per one cubic meter.

Investigations on breaking of floating ice were also performed on the Obsk reservoir. A different type of water gun was used in these experiments. This gun generated a 30 mm diameter jet at 2000 kg/cm^2 of pressure. These investigations have shown that floating ice breaks with larger intensity than ice which rests on the ground. The rate of work of the gun was 6720 m^3/hr in this case at a cost of 0.01 rubles per one cubic meter. The higher effectiveness of this type of gun was attributed to the fact that it has a larger opening (30 mm) than the IV-5 gun which has a 11 mm diameter opening.

The IV-5 water gun generated a water jet at 8000 kg/cm^2 of pressure. Investigations were performed at 3000 kg/cm^2; the maximum air injection pressure into receivers was 60 kg/cm^2.

The other type of gun generated a jet at 2000 kg/cm^2 of pressure pulses using 2.5 liters of water. Each were fired in 3 sec intervals. At higher pressures the ice tended to prick out at the opposite face of the specimen and the higher the pressure, the more pronounced is the wedge-like shapes of the jet. The experiments showed that the pulsed water guns can be successfully used in breaking floating ice in order to lengthen the navigation periods.

On rivers and lakes where the ice thickness seldom exceeds 0.5 to 0.6 meters, water jets could be used to enhance the ability of ships to navigate ice according to Tokeev. For navigation in ice which is more than 0.6 m thick (northern latitudes), it would be necessary to install the water jets in the bow section of ice breakers so that the ice can be cut and broken. For breaking very thick ice, it would be useful to employ the largest water jets in order to weaken the ice and to facilitate ice breaking operations.

Upper Mississippi Icebreaker - UMR (Figure A-7)

The UMR Icebreaker is a system designed to break the ice into pieces, remove them from the channel in an orderly manner and then displace the broken ice on top of the fixed ice on either side of a channel.

Although the emphasis was directed towards the materials handling aspect of this concept, all features for operation were incorporated in the preliminary design (Coburn).

The device consisted of a barge with an ice fracture mechanism, ice conveyors, and power supply machinery. It was sized to carry the full ice load with approximately one foot change in draft and a trim of about one degree.

In operation, the barge was pushed by a river type buoy tender. The ice fracture mechanisms, which are hydraulic impactors, crack and weaken the ice in front of the barge. As the barge progresses, a submerged bow ramp contacts the underside of the ice which is lifted and broken. The ice is forced up this ramp by the thrust of the pushing vessel. The conveyor system, powered from within the barge, brings the ice aft and up, turns the ice outboard and deposits it on either side about 30 feet from the edge of the channel.

A control power plant, which consists of twelve 340 horsepower marine diesel engines and hydraulic pumps, provides hydraulic power for the conveyor system and fracture mechanisms. Such an arrangement, coupled with conservative design, gives a flexible power supply with high reliability. It is interesting to note that overall efficiency of the conveyor systems, expressed as the ratio of the ideal power necessary to elevate and redirect the ice to the installed power, is about 25%.

The fracture method needs more analysis and development work to prove its validity. Coburn, in referring to the UMR Icebreaker, the Explosive Icebreaker and the Mechanical Ice Cutter, advised that, "the relatively high projective cost makes this (UMR Icebreaker) the least desirable concept to pursue."

Alexbow Barge (Figure A-8)

In 1966, Mr. Scott E. Alexander of Polar Enterprises and Mr. J. Gordon German of German and Milne devised a configuration for icebreakers known as the Alexbow System or Hammerhead Bow (German).

The device shown in Appendix A (figure A-8) is a self-floating bow section which relies on the hydrodynamic lift on the ice created as the water flows over the submerged surface of the plow form in conjunction with the propagation of a crack ahead of the bow initiated by what is termed "the knife." Therefore, the structural loadings are very low and the required scantlings are considerably reduced from those associated with conventional forms of equal icebreaking capability.

There appear to be three distinct operating regions of the bow:

a. Stem region; generally that region forward of the Forward Perpendicular.
b. Shoulder region; generally that region in way of the maximum breadth.
c. Above water region.

The operation of a sharp splitter blade is a complex interaction between the forward end shape, resulting water flow and the type and quality of the ice being encountered. (According to Milne, the most desirable blade shape must still be determined.)

The shoulder region, i.e., approximately the outboard 10 feet of the Hammerhead, is a highly important region in the icebreaking process. It is the region of maximum ice loadings and therefore, the most susceptible to damage.

An extension of the low slope region, well above the waterline approximately equal to the average ice thickness, is necessary to allow more weight to be carried by the bow. As long as the required channel width is broken and only the wet underside of the ice contacts the shell, removal of the ice should employ a method of minimum energy expenditure, i.e., sliding outboard (see Milne p. 7).

Bubbler Systems (Figure A-9)

Bubbler systems consist of compressors and piping. The air bubbling pipes are installed along the keel and compressed air is pumped through the pipelines. Since tests have shown hull roughness has a significant influence on ice forces, the bubbler system was designed to prevent the high friction steel hull from making contact with the ice.

The U.S. Coast Guard has constructed some new 140-foot icebreaking tugs that have incorporated an air bubbler system as well as other innovations such as a new shaped bow and low friction coatings. Tests (Vance) have shown that the icebreaker can penetrate 22 inches of snow-covered plate ice in a continuous fashion and can ram through up to 30 inches of solid snow-covered plate ice. Limited testing indicated the vessel can penetrate unconsolidated pressure ridges up to 5 feet thick. Use of the bubbler system reduced the power required some 25 to 35% in level ice. The vessels also displayed a capability of penetrating brash ice up to 4 feet. thick in the shipping channel. Use of the bubbler system decreased the required power some 30 to 50% in brash ice. However, the tests showed the bubbler system appeared to be of little use in the ramming mode.

The system requires practically no personnel to operate it and should have few maintenance problems associated with it according to Morean (p. 23).

Mechanical Saws (Figure A-10)

The purpose of mechanical saws is to either weaken the ice or slice it in set grooves. The weakened ice sheet or sliced ice is then displaced by the hull of the ship or some other materials hauling process.

Saws are any rotating device with teeth that cut through the ice. Sabre saws, circular saws, chain saws and routers are examples of sawing devices. A scouring device is a protusion with a sharp tip that grooves the ice. The scouring device is similar to the teeth of the rotating saw except that the vessel itself provides the power instead of a motor that drives the saw.

The Russians have extensively studied mechanical saws and report that model tests show devices using saws on channel clearing devices requires 17 to 28% of the force to move a model of a typical icebreaker. However, there is no literature on full-scale devices in operation.

Almost identical devices as studied by the Russians were explored during the U.S. Coast Guard mechanical ice cutter development program. It should be noted that there are U.S. patents dating to the 1800's that describe devices similar to the Russian and U.S. Coast Guard work.

Saws and scourers have not been investigated for direct mounting on ships but rather on bow attachments or specialized material handling concepts.

Archimedes Screw Vehicle (Figure A-11)

The Archimedes screw concept of locomotion is based on the use of two large counter-rotating screws that have parallel axes in line with the direction of travel. This locomotion is literally the same as achieved by a wood screw being screwed into wood with a screw driver. When employed on an amphibious vehicle, the Archimedes concept is excellent in soft terrain such as mud, sand or slush ice.

The concept can be used either as an alternative to normal ship propeller propulsion by mounting the screw directly on the ship and running off ship power, or it can be used as a separate tug-like vehicle that can push or pull ships through ice and water.

The Archimedes screw works better in a soft pliable terrain than in water or on a hard material such as sheet ice. Hence, it is envisioned that it would only be used as an auxiliary vehicle or propulsion method to augment the propeller. While the concept dates back to the time of Archimedes, the U.S. Coast Guard first became interested in the device when the U.S. Army developed a design as a possible light amphibious vehicle to use in Vietnam. Although several prototypes were built and are in use by the Marine Corps, full-scale operational deployment has not been made.

In 1973, the U.S. Coast Guard became interested in the device as a means to augment ship movement through thick mush ice. A demonstration in the swamps at Parris Island impressed officials and subsequently an unsolicited proposal was received from Arctec, Inc. This proposal was not pursued presumably for funding reasons.

Mechanical Impact Device (Figure A-12)

This device produces fracture mechanisms that crack and break the ice in front of a ship. Breaking of the ice occurs due to bending stresses imposed by the concentrated load resulting from impact and also radial cracking due to the shock. Essentially, the devices are like breaking the ice with an ordinary hammer only the scale is much larger.

Three types of devices have been explored but there are many other variations. Pneumatic actuators and pile hammers are two possible methods. An electro-hydraulic fracture mechanism involving a rotating weight has also been explored.

There are a number of patents relating to this concept and it was seriously considered during the mechanical ice cutter development program by the Coast Guard. However, the complexity and resulting loss in reliability were serious drawbacks. There are no known operational uses for icebreaking although use of one of the concepts, pile drivers, is very common.

Water Hull Lubrication System

The purpose of the system is to reduce hull/ice friction on an icebreaking ship. Friction has been shown to be a major component of icebreaking resistance, especially when a ship is stuck or moving at slow speed.

The water hull lubrication is built into the sides of the ship at the ice line. Nozzles penetrate the hull at strategic locations where friction is considered to be the most such as the bow and midship. Water is supplied from the sea chest and pumped (engine and pump may be separate units from main propulsion) to the nozzles where it is sprayed onto the ice/hull surface. The system would be used continuously in ice but especially when stuck or when negotiating slush/brash ice.

Low Friction Hull Coatings

This item reduces the friction of the ice moving against the hull of a ship and thereby reduces resistance of a ship in all types of ice and modes of operation. A dramatic improvement in breakout (or start up) capability is obtained, such as when a ship is stuck in ice, because low friction coatings are particularly effective in reducing static friction. Besides reducing hull/ice friction, these coatings also protect the hull plating and weld seams from corrosion which will severely pit a hull and further severely degrade ice and open water performance.

The most successful low friction coatings are non-solvented polyurethane and epoxy. Both types are very sophisticated systems that require controlled conditions and special apparatus and skills. Because they are non-solvented they can be used in a contained space and, in fact, applications have been made on the hull of a ship with the work space enclosed. Hence, a controlled atmosphere is created assuring a good application which is sometimes difficult to guarantee with conventional coatings. Because coatings are a passive apparatus that are applicable to any ship, in or out of ice, their use is limited only by the cost of application.

In the early seventies, Finnish and U.S. Coast Guard (RPI) investigators almost simultaneously began searching for coating systems that would have the tenacity to withstand severe ice abrasion and also reduce ship resistance and hence improve performance. The Finns discovered Inerta, a non-solvented epoxy which was tried on the ship, Valdas, in 1973, with dramatic improvements that were compared against an uncoated sistership. The U.S. Coast Guard program began with extensive laboratory tests that climaxed with successful experiments of a non-solvented polyurethane in the USCGC RARITAN in 1974. Since that time, the Coast Guard has successfully tested both coating systems on numerous ships and has conducted model tests and cost benefit analyses which further bear out the effectiveness of the coating system.

Stem Knife (Figure A-13)

The Stem Knife is a rectangular profiled extension at the stem of the icebreaker. Essentially, it is a very dull knife blade added to the stem along the center line of the ship. The Stem Knife is a permanent addition to a ship and can be adapted to new construction or existing ships. The purpose of the Stem Knife is to reduce resistance when operating in a continuous ice sheet. Ramming performance may also be enhanced.

The Stem Knife slots the ice at its contact with the hull. Hence, the cover is broken by shear instead of cusping. The broken pieces are larger than regular cusps and flow past the hull with less rotation. In general, ice flow is smoother and consumes less energy.

The Canadians have experimented with Stem Knives on several different ships. In August 1976, model tests were completed at HSMB on the Canadian Polar VII.

Bow Ramp (Figure A-14)

The Bow Ramp concept reduces the resistance of a ship and provides for a clearer path. The idea is to systematically break the ice and then move the pieces under the adjoining ice field. The traditional cusping and subsequent crushing action of a regular icebreaker bow is reduced substantially, hence saving evergy.

The Bow Ramp can be designed into the bow of a new ship or added onto an existing ship. The ramps could be permanently attached. However, this would increase resistance in open water. A retractable or pivotable ramp would alleviate this problem but would create structural and mechanical complexity problems. Another mode would be to have the ramp built onto a barge which is temporarily attached and pushed by the ship.

Operation is simple since there are no moving parts. Three stems break the ice into larger chunks which are channeled by the ramps under water. The chunks are then kicked out and under the adjoining ice field.

2.2 General Overview of Selection Procedure

2.2.1 The Icebreaking Mission

The U.S. Coast Guard operates the nation's fleet of icebreakers, managed by the Ice Operations Program. There is a hierarchy of stated sub-objectives and goals which relate the program to overall Coast Guard objectives, but basically three types of services are provided by the program:

a. Facilitate waterborne traffic in ice-laden waters
b. Provide flood control and prevention assistance
c. Cooperate with other government agencies in polar regions

The geographic areas of operation are polar and domestic waters including: the Great Lakes, Midwestern and Northeastern inland waterways, Arctic East (Greenland), Arctic West (Alaska), and Antarctica.

Naturally, such diverse environments with different operating requirements have different facility needs. In general, the Ice Operations Program services, listed above, can be related to five basic "functions" that an icebreaking ship performs:

1. Channel Clearing - consists of breaking ice along a path so that non-icebreaking ships can use it. The ideal channel is completely clear of ice.

2. River Operations - involves operation in shallow water with current. Dislodging or prevention of ice-buildup and flood control is the primary need.

3. Response - involves traveling an ice-covered track between two points as quickly as possible (without regard for channel clearing) to perform breakout, search and rescue, aids to navigation, pollution clean-up, or other needs.

4. Platform Capability - involves transporting goods or personnel, use as a scientific facility, and support of aircraft operations.

5. Vessel Breakout - involves operation in close proximity to vessels stuck in ice. By reducing ice pressures or otherwise reducing hull/ice contact for the immobilized vessel, the vessel's ability to proceed is restored.

This report is only for proposed devices to be used on the Great Lakes. However, the methodology is applicable to other geographic regions.

2.2.2 The Attributes

Each alternative device requires a description so that it can be identified and analyzed to determine the consequences of its selection. This description requires specifying characteristics which have meaning to the decision maker. Ship performance characteristics were selected which were expected to best fulfill the identified needs for the icebreaker. These ship performance characteristics will be designated as the "attributes" of the device.

A list of operations-related system attributes were compiled from several references and interviews with icebreaker-experienced personnel at Coast Guard Ninth District offices in Cleveland. The attributes included:

1. Speed (knots)
2. Turning diameter (feet)
3. Maintainability (man-days)
4. Ice Displacement (percentage of ice removed from channel)
5. Maximum Level Ice Thickness in Continuous Mode (feet)
6. Maximum Level Ice Thickness in Ramming Mode (feet)

7. Track Width (feet)
8. Open Water Acceleration (ship lengths)
9. Endurance (hours)
10. Fuel Consumption (gallons per hour)
11. Availability (percentage)
12. Additional Training Required (man-days)
13. Cargo Capacity (cubic feet)
14. Passenger Capacity (number)

Availability is defined as the percentage of time during the ice season that the icebreaker with the auxiliary device is able to get underway and complete the icebreaking mission. Cargo Capacity is the amount of cargo in cubic feet which an icebreaker is capable of transporting. Endurance was defined as the number of hours during which an icebreaker can operate without returning to port. Fuel Consumption is the average fuel required in gallons per hour during the performance of the mission function. Ice Displacement is the percentage of ice removed from a track in a single pass measured at a distance of two ship lengths aft of the ship under conditions of minimal ice pressure due to current, wind, and other factors. Maintainability is the maximum length of time in man-days which will be required to return disabled gear to service. (The ship must be unable to operate in ice without the repair of this gear.) Maneuverability is the turning diameter in ice measured in feet. Maximum Ice Thickness is maximum thickness of first-year field ice which can be broken in (a) continuous mode of breaking and (b) ramming mode. Open Water Acceleration is the distance in ship lengths necessary to accelerate to ramming speed at full power. Passenger Capacity is the number of passengers which may be accommodated for scientific studies. Speed is velocity in knots in ice. Track width measures the width of the track in feet which can be broken in a single pass. Finally, Additional Required Training is the time in man-days necessary for formal training in use of equipment.

Specifying a value for each attribute identifies an icebreaker configuration. A change in any or all of the attributes' values change the configuration and, hence, describe different alternatives. If the metacentric height of a ship were decreased, for example, a new configuration and, therefore, a new member of the set of auxiliary devices would be identified.

The consequences associated with implementing a candidate alternative is designated an outcome. An outcome has, in general, several measures or dimensions. Speed, Open Water Acceleration, Fuel Consumption, Maneuverability, Cargo, and Passenger Capacity are attributes of the icebreaker; Ice Displacement, Maximum Ice Thickness, and Track Width are attributes of the physical environment; and Maintainability, Availability, Endurance, and Additional Training Required are measures of the resources required to complement the decision. Estimates of the magnitudes of the measures of these 14 attributes for a given alternative under a given mission function yield a 14-component outcome vector.

Each attribute possesses the following: (a) it is measurable and (b) its measurement is considered to be practical, i.e., the cost and usefulness of its measurement are consistent with achievement of needs, goals, and objectives.

2.2.3 Utility: The Value Problem

Evaluation and optimization of alternatives can be accomplished more easily with respect to a single criterion. No individual attribute can rationally be used as the only basis for a decision. The decisionmaker cannot optimize speed, acceleration, availability, and endurance separately and simultaneously. If the decisionmaker is to identify an optimal alternative, he must be able to relate speed, acceleration, availability, etc., to some scalar measure of goodness which is common to all criteria.

This multi-dimensional outcome must be transformed, therefore, into a single figure of merit. A scale which measures relative contributions to success of the mission must be identified, and a means for measuring the multi-dimensional outcome on this scale must be formulated so that evaluation and optimization of alternatives can be accomplished.

The needed scalar measure of relative contribution to success has been referred to in the literature by various names; system worth, figure or merit, cost benefit, and utility. Although there are some unfortunate historical connotations to the term utility, there are advantages associated with the continued use of a term whose historical development can be traced and with which a considerable body of theory has developed. Therefore, utility will be used to identify the scalar measure of relative contribution to success, i.e., of degree of fulfillment of needs, goals, and objectives.

The work of von Neumann and Morgenstern, originally published in 1944, assumed that a rational man (our decisionmaker), in addition to possessing preferences for the outcomes of the alternative actions available to him, also possesses preferences for gambles involving these outcomes. With this assumption, they were able to formulate a set of axioms which, if accepted, guarantee the following:

1. A cardinal scale for measuring the decisionmaker's preferences (i.e., a utility scale) exists.

2. This utility scale is so defined that, if the decisionmaker chooses that alternative with the highest expected utility, he will be acting in accordance with his preferences.

To explain the approach consider the following simplistic example: A person may either receive $150 or flip a coin, receiving $200 if heads show up, receiving $100 if tails show up. This example raises questions like: are these 2 options indifferent to the decisionmaker; does he prefer the certain option of $150 if he desperately needs money; do his preferences remain unchanged when we replace $100 and $200 by $1,000,000 and $2,000,000; and so on.

A fundamental issue in utility theory is the introduction of the following lottery. We confront the decisionmaker with a "certainty" option, e.g., he can choose to receive $150 with 100% certainty. Next we confront him with 2 extremes, (say) receiving $500 with chance p, or $10 with chance 1-p. We may expect that a "rational" decisionmaker from whom the stakes of this lottery are not extremely high, will select p such that it solves the following equation:

$$150 = p500 + (1-p)10 \qquad \text{(see Appendix B)}$$

$$\text{or} \quad p = 14/49$$

A risk-averse person, however, will trade in the certainty option only if the chance of a good outcome ($500) increases above 14/49. A risk-prone person prefers the lottery even if $p < 14/49$. So the decisionmaker's risk attitude is measured by the value of p in the lottery that is substituted for the certainty option.

In order to further illustrate the above concept, consider the following hypothetical "game." The ship captain (decisionmaker) is faced with a certain situation in which more speed is desirable to obtain a goal, e.g., safe passage. Assume nature behaves in a manner which can be simulated by flipping a fair coin. If the coin turns up "heads," the result will be favorable, i.e., gain speed. Otherwise, the result will be unfavorable, i.e., lose speed, e.g., if the result of flipping the coin is "heads," the captain gains 0.5 knots; if the result of flipping the coin is "tails," the captain loses 0.2 knots. Furthermore, assume that the captain can at any time refuse to play this game, i.e., continue at present speed. Most captains would play this game.

Suppose, however, that instead of 0.5 knots and 0.2 knots, the "stakes" were increased as indicated in the following table:

GAIN	LOSE
0.5 knots	0.2 knots
1.0 knots	0.4 knots
2.0 knots	0.8 knots
4.0 knots	1.6 knots
8.0 knots	3.2 knots

(Each pair of gains and losses is called a "Lottery." This term is defined in Appendix B.)

Most captains would lose their enthusiasm for this game as the stakes increased, and they would refuse to play at some point, e.g., any speed loss over 1.0 knots might be certain death. What takes place may be explained in terms of the utility, i.e., the worth of "speed." At low stakes, the utility of the amount to be gained is greater than the utility associated with the amount to be lost. When the stakes increase until one is no longer willing to play, the utility of the amount to be lost becomes greater than the utility of the amount to be gained. In this game situation, knots do not truly measure worth, especially when large amounts may be gained or lost. This can be the only explanation since the probabilities of gaining and losing and the ratios of the speeds does not change as the stakes change.

The implication of the foregoing is that the quantities of speed associated with outcomes may not be an appropriate measure of the relative desirability of alternatives. This type of situation illustrates

that a linear relationship between speed and desirability does not always exist. This nonlinearity becomes especially important when relatively large changes in speed are involved and relatively large uncertainties characterize outcomes.

Similar arguments can be made to demonstrate that other measures (feet, man-days, ship lengths, gallons per hour) also do not always provide a linear measure of relative worth. This nonlinearity between usual measures of attributes and relative worth is a further indication (in addition to the multi-dimensionality of outcomes) of the need for a utility scale.

The implementation of this methodology, based on maximizing expected utility, depends on explicit probabilities and utilities obtained by quantifying human judgment. The discipline of psychophysics has been, for many years, developing techniques for obtaining quantitative subjective responses to physical stimuli (Stevens). In the psychophysical laboratory, subjects are asked to subjectively assign numbers to physical stimuli such as the intensity of light or sound or the weight of objects. For each type of stimulus, the relationship between the physical measures and the subjective responses shows remarkable consistency from time to time for the same subject and from subject to subject.

The results in the psychophysics laboratory are relevant to decision theory, for as Stevens points out, "it seems clear that utility, like brightness is the name of a response of a human organism to an external configuration of the environment. In this sense, money (or speed) is as much a stimulus as a light wave. Light gives rise to brightness and money gives rise to utility only because both these stimuli interact with human beings. The problem is to assess the product of these interactions."

Utility functions for non-monetary criteria have been reported. For example, the National Data Buoy Development Project, managed by the U.S. Coast Guard, explicitly used utility functions to evaluate alternative designs of an ocean buoy system to obtain and process environmental data; the relative worth curves for characteristics of the measurements and of the buoys were elicited from the scientific agencies who are to use the output of the data system.

The utility associated with an outcome is a function of the set of decision criteria, i.e., attributes

$$U = u(y_1, y_2, \ldots, y_j, \ldots, y_n) \qquad (1)$$

where U = utility associated with o n alternative
y_j = a decision criterion, a dimension of an outcome
$u(\ )$ = utility function over (y_j)

For the practical evaluation of utility functions, some assumptions about their shapes must be made. A fundamental issue is whether multi-attribute utility functions can be separated into independent parts. An independence model with an additive structure is:

$$u(y_1, y_2, \ldots, y_n) = \sum_{i=1}^{n} w_i u_i(y_i) \tag{2}$$

This means that u_i, the utility of attribute i, does not depend on the value of the other attributes. Moreover, this equation specifies that elementary utilities $u_i(y_i)$ can be simply added, after scaling by means of w_i. The additive independence implies that the curves are parallel.

If the valuewise dependence of the effects of the attributes was taken into account, the number of conditions to be evaluated becomes extremely large. For example, if there are only ten attributes and if it is necessary to consider six representative magnitudes of each attribute, then there are 6^{10} or more than 60 million magnitudes of utility to be assigned. If, on the other hand, independence is assumed so that each utility may be formulated by assigning a utility to each of the six magnitudes, then there are only 60 magnitudes of utility to be assigned. The ten resulting utility functions can be used to evaluate all outcomes which can be estimated during analysis. Valuewise independence is assumed because the methodology and model must be manageable.

Preliminary tests for independence on two subjects (based on their willingness to cooperate in the experiment) were performed after the utility functions were obtained. Although these tests were not conclusive, they indicated dependence to some degree.

The test involved a determination of a tradeoff value of one attribute paired with another. Speed was chosen as a primary attribute to be paired with all other attributes in twin. For each pairing, Speed was first set at a highly desired value (15 knots), and the second attribute was set at a low, undesirable value. With all other attributes set at some arbitrary low value, the subject was asked to identify the amount of speed he would trade off to obtain an arbitrarily determined highly desirable value of the second attribute. The process was repeated with the remaining attributes held at arbitrary high levels. Only if the results were the same for both tradeoffs could the pair (speed and attribute "n") be considered independent of the others.

The test results for one decisionmaker indicated that no pair is independent. For the other decisionmaker, four pairs of attributes were determined to be independent. These were availability, open water acceleration, endurance, and additional training. However, it should be noted that in the former decisionmaker's case, maximum ice thickness (ramming), availability, open water acceleration, endurance, fuel consumption, and maintainability were within ten percent of passing the independence test.

It is to be emphasized that no assumption concerning independence of the attributes within the analysis model is being made. Changing a control variable, such as length of the ship, number of engines, displacement, etc., can cause changes in many of the attributes, such as speed, fuel consumption, acceleration, etc. The attributes may be highly interrelated. It is only in their utility, in relative contribution to success, that independence is assumed.

Each attribute is characterized by a critical interval on its scale of measurement in which the utility of the attribute is very sensitive to changes in the magnitudes of the attribute. This interval of sensitivity results from such factors as (a) the characteristics of the requirements, (b) customer specifications, (c) the state-of-the-art, (d) availability of resources.

The critical interval includes the magnitude of the attribute which may be specified as a system requirement. For example, "a speed capability of three knots or faster" may be specified for channel clearing in brash ice. This point is a threshold which separates the desirable magnitudes of the attribute from the undesirable magnitudes of an attribute. The set of thresholds associated with the attributes may be termed a "threshold vector."

The minimum value for the utility scale is analogous to the natural origin found in psychophysics. "In the measurement of such attributes or attitudes, esthetics, preferences, and value, the natural origin occurs within the series and can be described as a neutral point such that all stimuli or individuals in one direction are favorable, pleasant, liked, or wanted as the case may be, whereas all those on the other side are unfavorable, unpleasant, or not wanted" (Torgerson).

The utility functions describe the value of utility given the attribute on an arbitrary scale of different attribute levels. They are determined using several key points including the maximum and minimum values of the attribute, the threshold or point of separation of desirables from unacceptable values, and the most preferred value.

Utility functions were obtained for each attribute/mission function pair through interviews with icebreaker operators. The interviewee was first asked to identify the threshold and the most preferred values. These two points were assigned a utility of 0 and 10.0 respectively. The two points established the bounds for the first in a series of "lotteries." (See Appendix B.) Subsequent bounds were selected based on response to the lotteries.

A lottery for formulating utility functions involves two values of the attribute which are each assigned a probability of occurrence of 0.5. The interviewee is asked to identify the minimum value of the attribute which he would accept in order to avoid participation in the lottery. The value chosen is assigned a utility which is the average of the utilities in the lottery. The lottery will be repeated with different bounds as necessary to determine additional points on the utility function. The result of a series of lotteries is a completed form as shown in figure 2-1 on the next page.

An expression which combines information concerning the utility of outcomes and the probability of outcomes into an estimate of expected utility is:

UTILITY FUNCTION FORM

		ANSWER	UTILITY	ANSWER LABEL
	[illegible]	22	5.0	A
	20	21	2.5	B
	22	23	7.5	C
[illegible]	B 21	21.5	3.75	D
[illegible]	A 22	22.5	6.25	E
[illegible]	T 20	20.5	1.25	F
[illegible]	C 23	23.5	8.75	G
23	B 21	22	5.0	H

[illegible]ION FUNCTION Channel Clear ATTRIBUTE Max.Ice Thickness Cont.

BOUNDS		ANSWER	UTILITY	ANSWER LABEL
[illegible]	Threshold 4	3	5.0	A
3	T 4	3.5	2.5	B
1	A 3	2	7.5	C
3	B 3.5	3.25	3.75	D
2	A 3	2.5	6.25	E
[illegible].5	T 4	3.75	1.25	F
1	C 2	1.5	8.75	G
2	B 3.5	3	5.0	H

[illegible]ION FUNCTION Channel Clear ATTRIBUTE O.W. Acceleration

FIGURE 2-1

FORM TO OBTAIN LOTTERIES

$$U_i = U\{u(y_j)_k,\ f(y_j)_{ik},\ p_k\} \tag{3}$$

where U_i = expected utility associated with Alternative i

$U\{\ \}$ = functional notation

$u(y_j)_k$ = set of utility estimates, and

p_k = weights over the mission functions

$f(y_j)_{ik}$ = probability density functions containing information on the relative likelihood of different levels of the attribute occurring

; ith alternative, jth attribute and kth mission function

The analysis was applied independently to each of the five mission functions. The mission function weights, p_k, allow the model to reflect the relative importance of one mission function over another. For instance, if a particular mission function was performed at a lesser yearly rate than another, the weight given to that mission function would be lowered thereby reducing its contribution to the overall utility by some amount. Of course, other factors must be taken into consideration such as the costs incurred when the mission is aborted, e.g., property losses, environmental damage, lost cargos, etc. Section 2.6 explains the mission function weights in greater depth.

For a specific attribute/mission function pair, the density function, $f(y_j)_{ik}$, is the probability that a value of an attribute will occur given a specific alternative. These functions have a distribution over the range of the attributes which is determined based on available technical information about the alternative devices.

2.2.4 Scaling the Utilities

The utility function of each attribute is formulated independently of the other attributes. The utility of a one ship length turning diameter, for example, measures preference to other turn diameters but has no established relationship to preferences for ice displacement or speed. The scale factor for each utility function has been arbitrarily defined without considering the other attribute or their utilities.

If the utilities of the various attributes are to be combined in the computation of expected utility, it is important that preferences for all attributes be measured on the same scale of utility. Analogously, we cannot add the costs of a variety of items if the various costs are measured in dollars, francs, pounds, pesos, etc. We cannot compute mean temperatures if some of the data are in degrees centrigrade and some are in degrees fahrenheit. We need, therefore, to modify the utility functions to ensure that the utility scale used to measure preferences for various magnitudes of y_1 is the same scale being used to measure preferences for various magnitudes of y_2, y_3, ..., y_4, ...

Utility is defined on a cardinal, or interval scale (see Appendix B). The origin and scale factor are arbitrary and computing expected utilities is meaningful. For a cardinal utility, a linear transformation is permitted (Lifson), i.e., the transformation does not affect a decision based on expected utility.

$$\text{Let } u_j\,(y_j) = a_j\, u_j'(y_j) + b_j \tag{4}$$

where $u_j\,(y_j)$ = scaled utility function
$u_j'(y_j)$ = unscaled utility function
a_j, b_j = constants to be determined for each $u_j\,(y_j)$

This transformation equation, Equation (4), requires identifying the two constants a_j and b_j for each j.

All threshold values have been assigned a utility of zero and the most preferred values were assigned a value of 1. Therefore:

$$u\,(y_{Tj}) = 0, \text{ when } u'(y_{Tj}) = 0 \tag{5}$$

where y_{Tj} is attribute value at the threshold.

If the following relationship holds:

$$u\,(y_{Mj}) = w_j, \text{ when } u'(y_{Mj}) = 1 \tag{6}$$

where (y_{Mj}) is attribute value at the most preferred level, then substituting in Equation (4):

$$0 = (a_j)\,(0) + b_j \tag{7}$$
$$w_j = (a_j)\,(1) + b_j \tag{8}$$

Under these conditions, Equation (4) becomes

$$u_j\,(y_j) = w_j\, u_j'(y_j) \tag{9}$$

If the constants, w_j, were known, the utility would be properly scaled. In order to determine the w_j, it is necessary to weight the attributes according to achievement of goals and objectives fixing the value of "each" attribute at its most preferred level. These weights are the needed constants, w_j, that complete Equation (9) above. This requires asking additional questions of the same people interviewed to determine the utility functions.

The method used to obtain the relative weights between attributes, which has been directly adapted from Saaty, converts the most preferred value of the utility functions to a common scale by assigning relative weights for each attribute. It has been noted in Saaty that "7" is the maximum number of elements which can be compared with any reasonable (psychological) assurance of consistency. So the attributes were first decomposed into two clusters.

To obtain the weights, a matrix was set up using two groups of seven attributes with the attributes in the same order forming the first row and column of the matrix (see figure 2-2). The interviewee compared each pair of attributes in the matrix and assigned a numerical value from one to nine which was a measure of the relative importance of the row attribute to the column attribute. A one indicated equal importance; a nine, absolute importance of the row attribute over the column attribute. In cases where the

	Ice Displacement	Maximum Ice Thickness, Ramming	Maximum Ice Thickness, Continuous	Open Water Acceleration	Speed	Track Width	Maneuverability	Weights from Eigenvector Analysis
Ice Displacement	1	6	1/2	6	4	2	3	.182
Maximum Ice Thickness, Ramming	1/6	1	1/4	1	1/4	1/7	1/6	.025
Maximum Ice Thickness, Continuous	2	4	1	5	5	3	3	.236
Open Water Acceleration	1/6	1	1/5	1	1/3	1/5	1/5	.025
Speed	1/4	4	1/5	3	1	1/4	1/3	.051
Track Width	1/2	7	1/3	5	4	1	2	.133
Maneuverability	1/3	6	1/3	5	3	1/2	1	.097

RELATIVE IMPORTANCE OF MATRIX 1 OVER MATRIX 2 3

	Availability	Endurance	Fuel Consumption	Maintainability	Additional Required Training	Weights from Eigenvector Analysis
Availability	1	7	6	3	4	.121
Endurance	1/7	1	1	1/5	1/4	.012
Fuel Consumption	1/6	1	1	1/5	1/4	.013
Maintainability	1/3	5	5	1	3	.066
Additional Required Training	1/4	4	4	1/3	1	.037

MISSION FUNCTION. Channel Clearing

FIGURE 2-2

WEIGHT MATRIX

column attribute was more important than the row attribute, reciprocals of the weights were assigned (1/3, 1/5, etc.). This procedure was repeated for each mission function.

After matrices were assembled, an analysis was performed which yielded the maximum eigenvalue for the matrix. (A detailed explanation of the method is given in Appendix C.) The eigenvector contains one component for each attribute in the matrix which is proportional to the relative weight for the corresponding attribute.

The following formulation of an objective function (see Lifson) is based on the decision rule to maximize expected utility.

Let U_{ijk} = the expected utility of y_j given Alternative i and mission function k.

If y_j is measured on a continuous scale,

$$U_{ijk} = \int_{-\infty}^{+\infty} u(y_j)_k \, f(y_i)_k \, dy_j \tag{10}$$

The probability density quantifies the uncertainty in the level of the attribute under mission function k if Alternative i is implemented. The operation represented by the above equation automatically incorporates this uncertainty into the final result. The probabilities of each level of attribute occurring are weighted by the corresponding utilities for that level. All the quantified information concerning uncertainty of performance with respect to y_j and concerning preferences for various levels of y_j is processed in the computation of expected utility.

Since valuewise independence has been assumed, we may obtain U_{ik}, the expected utility associated with Alternative i, and mission function k, by summing the set of $\{U_{ijk}\}$.

$$u_{ik} = \sum_j U_{ijk}$$

$$u_{ik} = \sum_j \int_{-\infty}^{+\infty} u(y_j)_k \, f(y_j)_{ik} \, dy_j \tag{11}$$

To obtain $E(u_i)$, the expected utility associated with Alternative i, the mission function weights, p_k, are incorporated as follows:

$$E(u_i) = \sum_k p_k u_{ik}$$

$$= \sum_k p_k \sum_j \int_{-\infty}^{+\infty} u(y_j)_k \;\; f(y_j)_{ik} \, dy_j \qquad (12)$$

This equation provides for the three measures of each attribute; the attribute level y_j, the probability measure $f(y_j)$, and the utility measure $u(y_j)$ as well as for the mission function weights. The information concerning uncertainty and relative worth is combined into a rational, theoretically sound decision rule.

2.3 Obtaining the Utilities

The following "operational" personnel were interviewed to obtain utility functions for the 14 attributes:

a. CAPT G.D. Hall, CDR A.D. Rosebrook and LT H. Bohen; USCGC MACKINAW (WAGB83)
b. LT S.J. Norman and LT R.E. Heins; USCGC BISCAYNE BAY (WTGB104)
c. LT J. Embler; USCGC KATMAI BAY (WTGB101)
d. CWO2 J.S. Sebastian; USCGC RARITAN (WYTM93)
e. LCDR T.D. Brennan; Commandant (G-OMI)
f. LCDR C.B. Mosher; Commandant (G-OMI); CDR W.A. Monson; USCGC WESTWIND (WAGB281)
g. LT R. Young; USCGC MARIPOSA (WLB397)
h. LCDR P.E. Sherer; USCGC BRISTOL BAY (WTGB102)
i. CDR C.S. Parks; USCGC BRAMBLE (WLB392)
j. LCDR C.K. Bell; Ninth Coast Guard District

The decisionmaker, i.e., operational manager, was presented with the necessary details to familiarize him with the technique. Once certain that the decisionmaker fully understood the methodology, the analyst presented him with the following descriptions of each mission function along with a scenario:

1. Channel Clearing - Passage of an icebreaker through a channel or track for the purpose of preparing it for subsequent use by a non-icebreaking ship.

   Scenario - Cutting a track through 3 feet of brash ice with less than 5 inches of refrozen brash ice present. The brash ice channel is 1.5 times the width of the icebreaker. A ship is following one mile astern.

2. <u>Breakout</u> - The ability of an icebreaker to free a vessel beset by ice pressure.

<u>Scenario</u> - Freeing of a vessel beset in close proximity to a pressure ridge which will require penetration by the icebreaker. The channel has been closed in by ice movement. Field ice around the beset vessel is 14 inches thick. Heavy ridges of refrozen brash ice 5 feet thick are located along each side of the vessel. An open pool is located aft of the ship and 3 feet of brash ice of width less than the ship's beam is directly ahead. Transit to the scene is not included in this scenario.

3. <u>Response</u> - Transit between 2 points as fast as possible with no regard for channel clearing for the purpose of performing SAR, pollution cleanup, breakout, etc.

<u>Scenario</u> - Three hypothetical situations will be given equal weighting.

1. Transit through 3 feet of brash ice with 6 inches of refrozen brash.
2. Transit through 15 inches of first-year field ice.
3. Open water transit.

4. <u>River Operations</u> - The breaking up of ice jams in rivers and harbors for purposes of flood control and ice damage prevention.

<u>Scenario</u> - Working in a restricted channel to clear an ice jam of refrozen brash 5 feet thick.

The decisionmaker was asked to give his most preferred value and the threshold value (or aspiration level) for each attribute. The level at which the interviewee thought himself to be indifferent to a 50-50 lottery between these two levels was assigned a lottery of 0.5. The level of indifference was then determined between this level and the threshold which gave a lottery of one half of 0.5 or 0.25. This process was repeated for all other in-between lotteries, i.e., 0.75, 0.375, 0.625, 0.125 and 0.875. Figure 2-1 shows the form used to tabulate answers to the lotteries.

Utility data was collected for each attribute/mission function pair. In all, 910 utility functions had to be developed for all the 13 decisionmakers. The data was entered into disk files and plotted on the R&D Center's Data General Computer.

Utility function data are plotted in Appendix F. The data was fitted with a piece-wise linear curve with a lower bound of zero utility (at the threshold) and an upper bound of one (at the most preferred value). Utility functions for different individuals are plotted on the same axis. Some curves are drastically different from others because the decisionmaker's preferences were influenced by the type of ship they were assigned to or were most experienced with.

As mentioned in section 2.2.3, the utility functions needed to be converted to a common scale for each decisionmaker. A matrix, (see figure 2-2) was set up using two groups of attributes. Ice Displacement, Max Ice Thickness Ramming, Max Ice Thickness Continuous, Open Water Acceleration, Speed, Trackwidth, and Maneuverability were assigned to Group 1. Availability, Endurance, Fuel Consumption, Maintainability and Additional Required Training were assigned to Group 2. The first group was mainly non-cost related, i.e., operational. The second was oriented towards administrative or resource related attributes.

The interviewee compared each pair of attributes in the matrix and assigned a numerical value from 1 to 9 which was a measure of the relative importance of the row attribute to the column attribute. A one indicates equal importance; a nine, absolute importance of one attribute over the other attribute. In cases, where the column attribute is more important than the row attribute, the reciprocal of the weight was assigned to the inverse comparison (1/3, 1/5, etc.).

The two groups were weighed in the same manner and combined using the method outlined in Section 2.2.4 and in greater detail in Appendix C. The weights were then multiplied by the appropriate utility function thereby scaling the functions to a common scale.

2.4 Determining the Probability Density Function

The probability density was assumed to be of the form of the Beta Distribution:

$$f(x) = \frac{1}{B(v,w)} \left(\frac{x-a}{b}\right)^{v-1} \left(\frac{b-(x-a)}{b}\right)^{w-1} \tag{13}$$

where:

$$B(v,w) = \int_0^\infty u^{v-1} (1-u)^{w-1} \, du$$

$$a \le x \le a + b$$

(a is a location parameter and b is a scale parameter with shape parameters $v > 0$, $w > 0$)

The engineer decided where the device was most likely to operate and this point was taken to be the mode of the above distribution, where the mode $= (v-1)/(v + w - 2)$. In addition, the engineer selected the lowest and greatest point with which the device is capable of operating and these were called the upper and lower bounds.

For purposes of comparison with auxiliary devices, the 140' WTGB was considered to be 100% available. The availability of the device/ship combination was then the availability of the device alone. The current level of man-hours of repair required on the ship was used as the zero level of the "Maintainability" attribute. In other words, only the man-hours required to repair the auxiliary device was estimated. "Additional Required Training" referred to all training beyond that currently being done which pertains to the use of the auxiliary device. All other attributes were measured in terms of actual ship or ship device values.

For purposes of comparison with auxiliary devices, the 140' WTGB was considered to be 100% available. The availability of the device/ship combination was then the availability of the device alone. The current level of man-hours of repair required on the ship was used as the zero level of the "Maintainability" attribute. In other words, only the man-hours required to repair the auxiliary device was estimated. "Additional Required Training" referred to all training beyond that currently being done which pertains to the use of the auxiliary device. All other attributes were measured in terms of actual ship or ship device values.

The "Ramming Speed" Attribute was assumed to be 12 knots. Speed for channel clearing and river operations was assumed to be 5 knots. Breakout was calculated for 14 inches of level ice and "Response" was calculated for 15 inches of level ice. Maneuverability was measured using turning diameter in feet. Track width was measured in feet and cargo capacity in cubic feet. Speed was measured in knots. Open Water Acceleration was the distance in ship lengths necessary to accelerate to ramming speed at full power. Ice displacement was the percentage of ice removed from a track in a single pass measured at a distance of two ship lengths aft of the ship under conditions of minimal ice pressure due to current, wind and other factors.

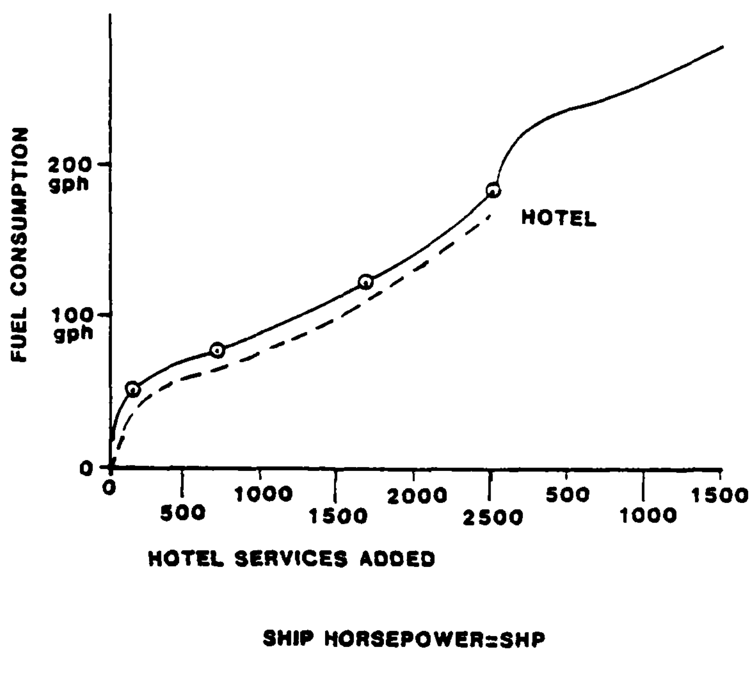

FIGURE 2-3
FUEL CONSUMPTION VS HORSEPOWER

Fuel consumption was the average fuel required in gallons per hour during the performance of the mission function. Figure 2-3 shows a graph relating fuel consumption to horsepower. The points on the graph were obtained from LCDR A. Gracewski (Commandant (G-ENE-3)). At full power the 140' WTGB was assumed to burn 166 gallons per hour and 39 gallons per hour at 161 ship horsepower. Curves relative to this curve were estimated for each device as shown in figure 2-3. Speed was then directly related to horsepower.

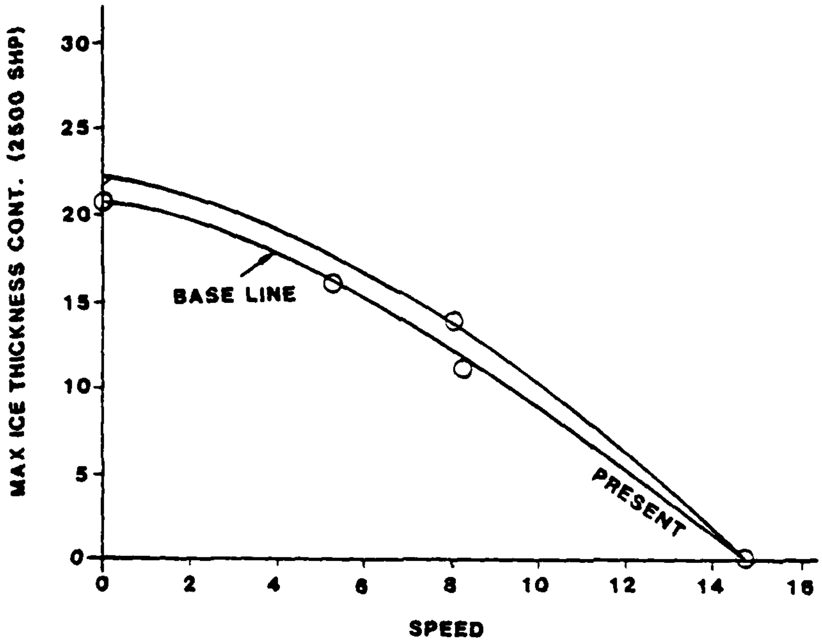

FIGURE 2-4
SPEED VS MAXIMUM ICE THICKNESS

Figure 2-4 shows a plot of speed versus maximum ice thickness at 2500 ship horsepower. The baseline curve was the 140' WTGB. Other curves for each device were drawn parallel to this curve. A change in speed therefore produces a change in ice thickness, and vice versa.

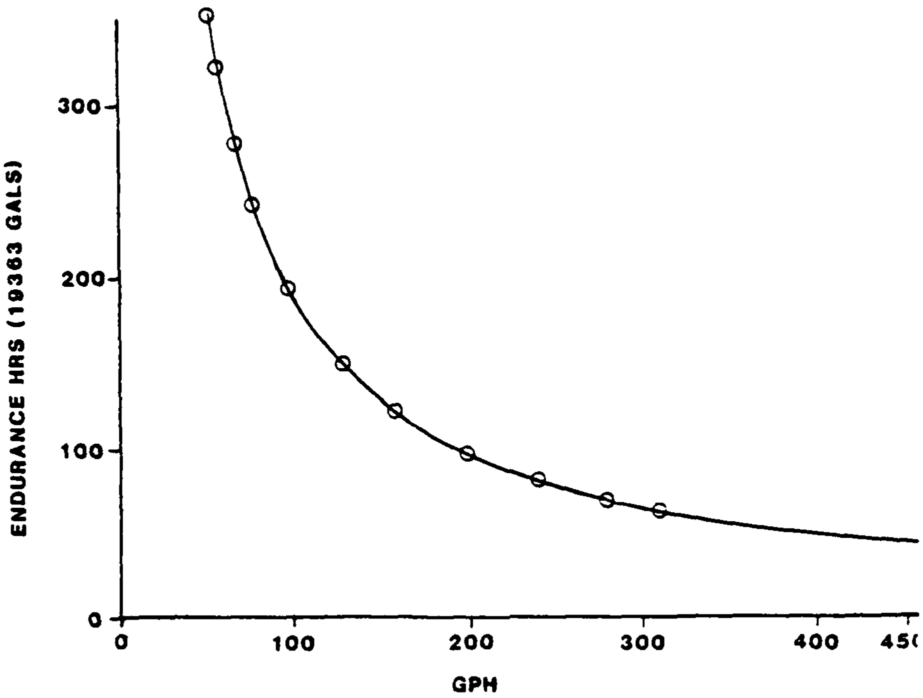

FIGURE 2-5
ENDURANCE

Figure 2-5 is a plot of endurance, defined as the number of hours during which an icebreaker can operate without returning to port, versus gallons of fuel consumed per hour underway. The various values for the endurance attribute were derived from this plot.

Tables 1 through 19 in Appendix D show the values for "Mode", "Upper" and "Lower" bounds selected for the various devices used to describe the probability densities. The values for the 140' WTGB with no auxiliary devices attached are also shown. This configuration was used as the "Baseline" in which all other configurations were compared.

2.4.1 Probability Density Function Data Analysis

Table 2 in Appendix D gives the values for the Hydroflusher device relative to the baseline, 140' WTGB. This device was thought to be somewhat useless for clearing big chunks of ice but it should do well with pieces under 2 feet in diameter. It was estimated that 3 jets per side of the ship would be needed given 300 to 500 total horsepower. As shown in the table, advantage was given to "Ice Displacement". Since the Hydroflusher

reduces friction, an advantage was also given for speed in level ice which increased response average speed from 6.3 knots to 9.4 knots. Side forces help to turn the vessel yielding better maneuverability, and Trackwidth remained nominal. Cargo capacity was penalized about 3000 cubic feet due to the space required for the machinery.

Mechanical Impact devices (table 3) showed a relative increase in Ice Displacement (ramming) of .15 feet and Speed increased a little over a knot. The device should shatter more ice so Trackwidth was increased by 2 feet. A small decrease in Turning Diameter can be observed and the Availability was down about 20% in Response and Breakout mode due to decreased usage under these mission functions. 120 horsepower was added for the machinery which decreased endurance by a proportional amount. Maintainability does not show any change because if the device became inoperable, the mission would still carry on without it. Cargo Capacity fell off somewhat because of the engine space required.

The Alexbow Barge (table 4) was designed to displace ice more effectively so Ice Displacement was rated about 40-50% higher across all mission functions. Turning diameter was also increased showing a reduction in maneuverability. Speed dropped slightly on the low end and Trackwidth was increased because the bow could be made wider than the ship. The horsepower was up slightly reflected in lower endurance readings.

Mechanical saws (table 5) are only used in Response and Breakout mode, i.e., level ice. Ice displacement increased considerably because large chunks of ice can be "kicked off" to the side. Maximum Ice Thickness Continuous went up by 10 feet, a substantial increase due to expectations from literature. The boat can effectively move as fast as the saws can cut the ice so therefore Speed increased about 3 knots. Trackwidth remained about the same but Maneuverability was penalized due to the saws being mounted out in front of the ship thereby increasing the length of the ship. Horsepower required increased, penalizing Fuel Consumption proportionally.

Hull Coating (table 6) increased Maximum Ice Thickness Ramming but did not affect Speed to any degree. The horsepower required decreased slightly due to the decrease in resistance. Most of the other factors remained nominal, i.e., values close to the 140' WTGB.

The ACV BOW (table 7) shows a modest increase in ice displacement whereas Ice Thickness increased by a large amount, i.e., 15 inches. Due to the large mass of the device, Open Water Acceleration slowed some but Speed increased due to the characteristics of the device. Trackwidth was optimum, i.e., utility one. Availability was penalized based upon our experience with skirt material and Maintainabiity was rated poor because it is very difficult to work with this device. Training was also penalized. A large amount of capacity was added because cargo can be piled on the deck of the ACV itself. The fan power added 1200 hp.

With the Pitching System (table 8) a small advantage was given to Ice Displacement and Speed. Ice Thickness increased along with Trackwidth because tests have shown the Pitching System tends to break wider channels. Cargo Capacity was dropped due to space required for machinery. 350 hp was used as motive power.

Lasers, (table 9) increased the Ice Thickness because of its ability to cut effectively. Speed increased accordingly. Quite a bit of horsepower was added in level ice to run the equipment; 3200 hp. Cargo Capacity dropped because of the space required by the laser equipment.

The Stem Knife (table 10) showed modest increases in speed and ice thickness. The rest of the values were nominal.

Water Jets (table 11) show increases in Ice Thickness and Speed based upon results found by previous tests at other facilities. Since the Water Jets can be swung out quite a ways, maneuverability improved significantly. Resistance was reduced because the ice is cut ahead of the ship. This device was penalized heavily in increased training required. The Cargo Capacity decreased, again due to space required for the machinery.

The Archimedes Screw (table 12) shows an increase in Ice Thickness and Speed because of its design characteristics. However, due to the digging action and its large mass, Open Water Acceleration decreased. Because of better traction, Maneuverability improved. Availability was moderate and Maintainability was below the nominal value. Cargo Capacity increased.

The Bow Ramp (table 13) does very well in displacing ice because it is designed to pack the ice to the side. Ice Thickness was reduced and Speed increased somewhat due to design features. Ice Thickness in ramming mode decreased while Ice Thickness in continuous mode increased somewhat. The Bow Ramp has a large mass producing drag in the water so Acceleration was decreased to account for this. The Trackwidth decreased because the Bow Ramp cannot hang too far out the side. More maintenance would be required for this device.

The Mechanical Icecutter (table 14) shows a substantial increase in Ice Displacement because it is supposed to cut smooth slabs of ice which should be kicked off more efficiently. Ice Thickness in ramming mode decreased but Ice Thickness in continuous mode improved due to the design features. The maximum cutting rate would be limited for this device so Speed decreased during Channel Clearing. Trackwidth increased because the cutters can be moved to increase the width of the track. However, the Maneuverability worsened because the ship is lengthened due to the cutting apparatus. The cutters were asssumed to consume 100 hp. More training would be required and the Cargo Capacity is increased.

The UMR icebreaker (table 15) shows increases in Ice Displacement and Maximum Ice Thickness in Continuous Mode, although Ice Thickness in ramming mode is slightly down. The device has a large mass so Open Water Acceleration is down a large amount. Turning diameter is below nominal values because the length is twice as long. The Availability was penalized because of all the machinery that would be required to complete the mission. The complexity of the device penalized the Maintainability as well as Additional Required Training. The horsepower required is 4800 hp.

The Bubbler System (table 16) shows moderate improvement in Ice Thickness and Speed. The Horsepower was 360 hp and the Cargo Capacity was reduced.

Water Hull Lubrication (table 17) shows improvement in Ice Thickness and Speed. 700 hp was added to lubricate the hull and more Cargo Capacity was added because the device/system does not require additional space.

The Explosive Icebreaker (table 18) has a moderate increase in Speed and a definite increase in Ice Thickness due to its design features. The Track Width improved slightly but Availability was penalized. Cargo Capacity improved.

The main advantage of Bilge Keels (table 19) is an increase in Ice Displacement. Ice Thickness Ramming was decreased along with Open Water Acceleration due to drag. Speed as well as all other values were nominal.

2.5 Overall Utility

The Probability Density function tables stored in computer files were retrieved as each device was analyzed. The computer program generated the appropriate Beta Distribution for each attribute/mission function/alternative device triple. Figure 2-6 shows a hypothetical probability density for a mission function/Turning Diameter pair. The spread along the Turning Diameter axis is a measure of the uncertainty felt about the estimates.

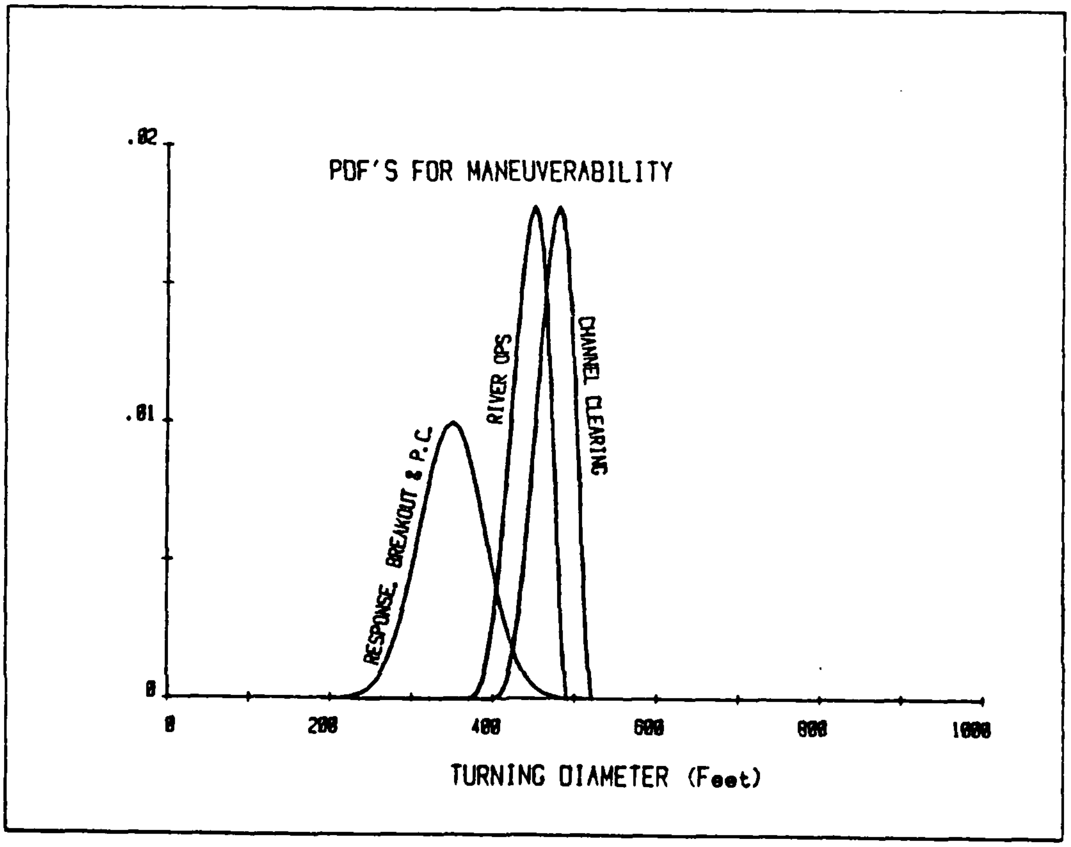

FIGURE 2-6
HYPOTHETICAL PROBABILITY DENSITY FUNCTIONS FOR MANEUVERABILITY

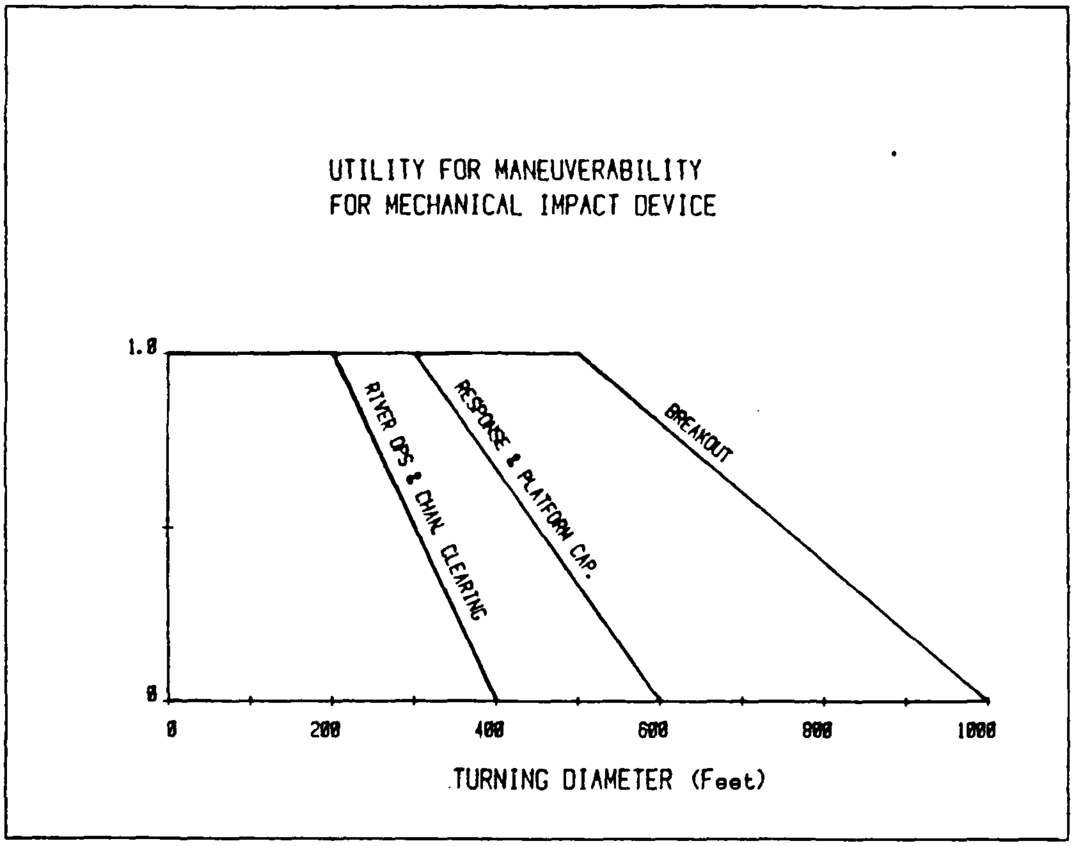

FIGURE 2-7
HYPOTHETICAL UTILITIES FOR MANEUVERABILITY FOR MECHANICAL IMPACT DEVICE

The above figure 2-7 shows a typical set of utilities for the attribute, Turning Diameter. The computer program linearly interpolates the utility function with the generated probability function and multiplies the interpolated point times the generated density point resulting in a new curve shown in figure 2-8.

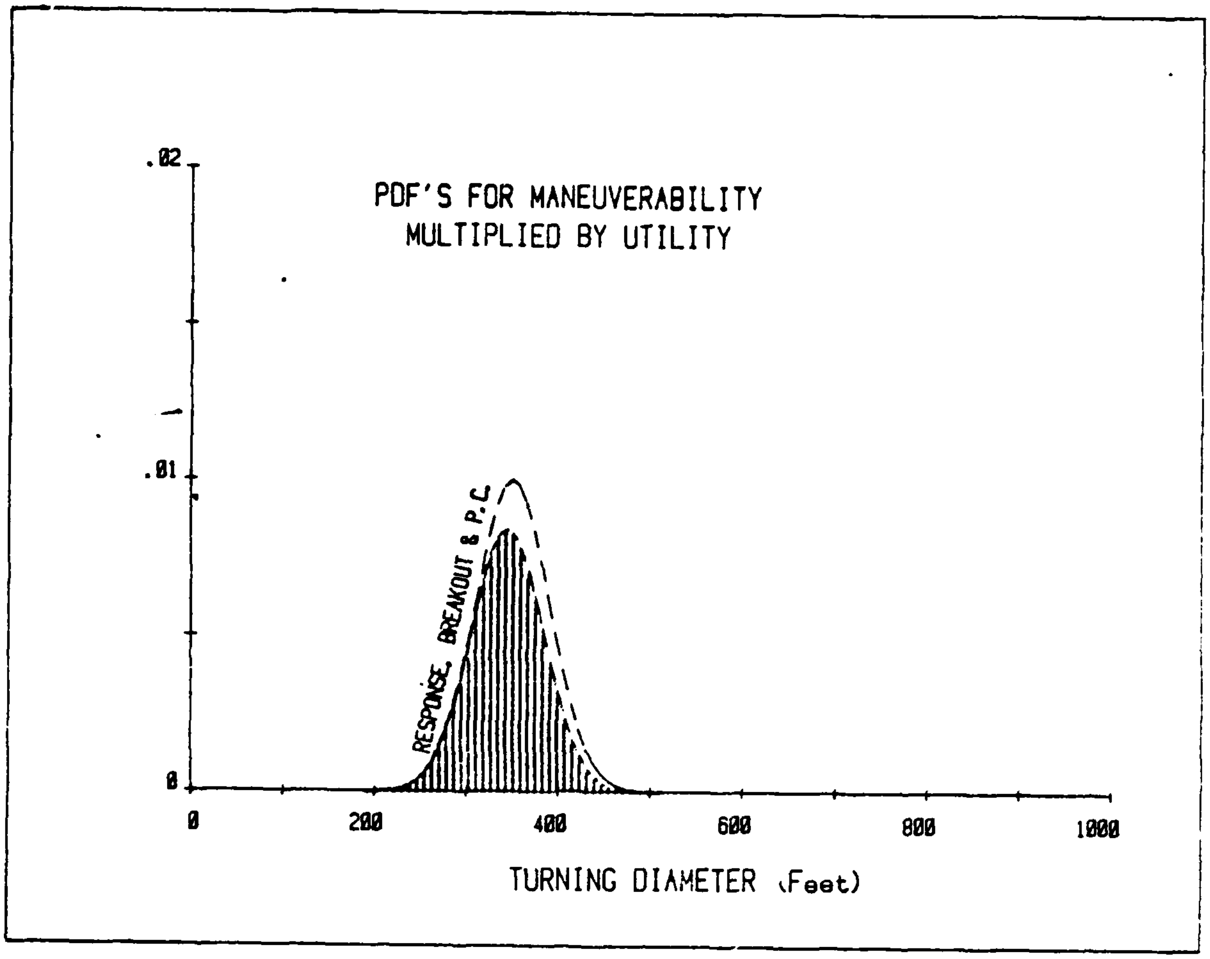

FIGURE 2-8
PROBABILITY DENSITY FUNCTIONS FOR MANEUVERABILITY MULTIPLIED BY UTILITY

The dotted curve is the density and the solid curve is the result of the interpolation-multiplication operation. This curve is numerically integrated to yield the desired expected utility of the attribute. This utility, termed a "raw" utility, is then multiplied by the scaling weight (Section 2.2.4).

After all the attribute/mission function pairs are processed in the above manner, they are multiplied by the mission/function weights to obtain a single index of worth for the alternative. The rest of the alternatives are similarly handled and finally they are ranked according to the relative worth.

2.6 Ranking the Mission Functions

The program manager assigned weighting factors, signifying their relative importance, for each of the mission functions as follows:

Channel Clearing	0.35
Breakout	0.30
Response	0.25
River Operations	0.05
Platform Capability	0.05

The "weighted" utilities are reproduced in the printouts found in Volume 2. Using these values, it is possible to hand-calculate new utilities for each device if the above weights are to be changed, e.g., multiply each utility on the bottom of the printout by the appropriate mission function weight and sum the results across to obtain a new expected utility for the device.

3.0 COMPARING ALTERNATIVES

Volume 2 contains copies of the computer results for the 19 alternatives adjudged by the 13 participants. A ranking of the devices based on highest expected utility is given for each decisionmaker. Additionally, a tally of the raw and weighted (scaled) utilities is given for each attribute/mission function pair for each device.

The raw utilities were obtained by multiplying the probability density times the utility function and integrating as described in Section 2.3. It is important to understand that these numbers have not been scaled so their magnitudes can be misleading. These numbers were included mainly for verification and should not be used for making comparisons.

The weighted utilities are simply the raw utilities multiplied by the eigenvector (or weights) that transforms the utilities to a common scale. The sum of these scaled utilities is presented at the bottom of the page for each mission function. A relatively large value for this sum would indicate that the device is expected to be more useful in the corresponding mission.

Each of the above mission utilities were multiplied by the appropriate mission function weights that were supplied by the program manager and tallied on the page that gives the ranking of all the devices. Of course, the mission utilities can be multiplied by other weights to yield a different ranking. This might be useful in checking the sensitivity of the mission weights to the final ranking of the devices.

The relative strength of the device to perform under a specific attribute across all mission functions can also be observed from the printouts. Again, one must be careful to use the weighted utilities, not the unscaled raw utilities when making comparisons.

It should be mentioned that the raw utility is a result of a complex interaction between the decisionmaker (operational manager) and the engineer who drafted the probability densities for each device, i.e., utility function multiplied by density function. Therefore, this as yet unscaled utility does not represent true preferences when comparing attributes and/or mission functions. It must be properly scaled to reflect preferences between attributes and across mission functions. This is not true for the mission function weights because they remain the same for all attributes. However, to compare the relative benefits for each mission function the analyst should carry out the multiplication of mission function weights times the final summed weighted utilities at the bottom of the page unless equal weighting is desired.

The utility is given as a number between 0 and 1; least preferred to most preferred. If the probability density lies outside the bounds of the utility function, a limiting value of 1 or 0 is assigned to the expected raw utility depending on whether the density is above or below the threshold. Most values that are 0 or 1 are a result of the density lying outside or very near the bounds of the utility function; a rare occurrence might result in the calculated value being exactly 0 or 1.

Ten of the thirteen individuals interviewed did not supply data for the fifth mission function, Platform Capability. The Cargo Capacity and Passenger Capacity attributes were not considered because they refer only to Platform Capability. Platform Capability was added prior to the interviews with LCDR Sherer, LT Bell and LT Burrows. In order to provide consistent results, the three aforementioned individual's utilities and weights were averaged for the Platform Capability Mission function and presented in the printouts in Volume 2 for the ten individuals that had not supplied data for the Platform Capability Mission Function. The computer printouts denote this by displaying a double asterisk at the top of the Platform Capability column near the heading. Since this adds an equivalent amount of utility for each of the ten individuals, the final relative ranking of the devices is not affected by this feature.

Figure 3-1 shows graphically the result of averaging all the final utilities for all the decisionmakers. Again, one must be careful in interpreting this graph because weights are equal for each of the 13 participants. However, this graph does give a "feel" for the overall results. The Pitching System and Hydroflusher are the most preferred devices while the Upper Mississippi River (UMR) Icebreaker is clearly inferior.

Figure 3-2 gives the average ranking for each device. The Pitching System appears to be the clear "winner" with the Hydroflusher and Stem Knife second. The UMR Icebreaker and the Explosive Icebreaker are nearly tied for last place.

We wish to gain information concerning the degree to which the 13 participants were in agreement concerning the ranking of the 19 devices. This agreement, among the decisionmakers, can be measured by Kendall's (1948) Coefficient of Concordance, W.

Table 3-1 shows the actual ranks given to the 19 devices by 12 of the decisionmakers. Let $n = 19$, the number of columns or devices, and $m = 12$, the number of rows or decisionmakers. The Coefficient of Concordance, W, is given by:

$$W = \frac{\text{Column Sum of Squares} - (1/m)}{\text{Total Sum of Squares} + (2/m)} \tag{14}$$

A value of 1 indicates perfect agreement while a value of 0 results in complete disagreement.

The decisionmakers were separated into 3 clusters; WTGB, MACKINAW and 180-foot type ships. The coefficient for the first 4 decisionmakers, i.e., WTGB experience, was 0.574. The MACKINAW group yielded an agreement of 0.453 and finally the 180-foot class had a coefficient of 0.596. The overall agreement was 0.541.

A high value of W may indicate that the decisionmakers are applying essentially the same standard to the devices being ranked, regardless of other considerations. If the decisionmakers cannot agree in their rankings, then it may be because the devices do not differ sufficiently in degree, e.g., if differences are so small that they cannot be reliably discriminated, then we cannot expect the decisionmakers to agree.

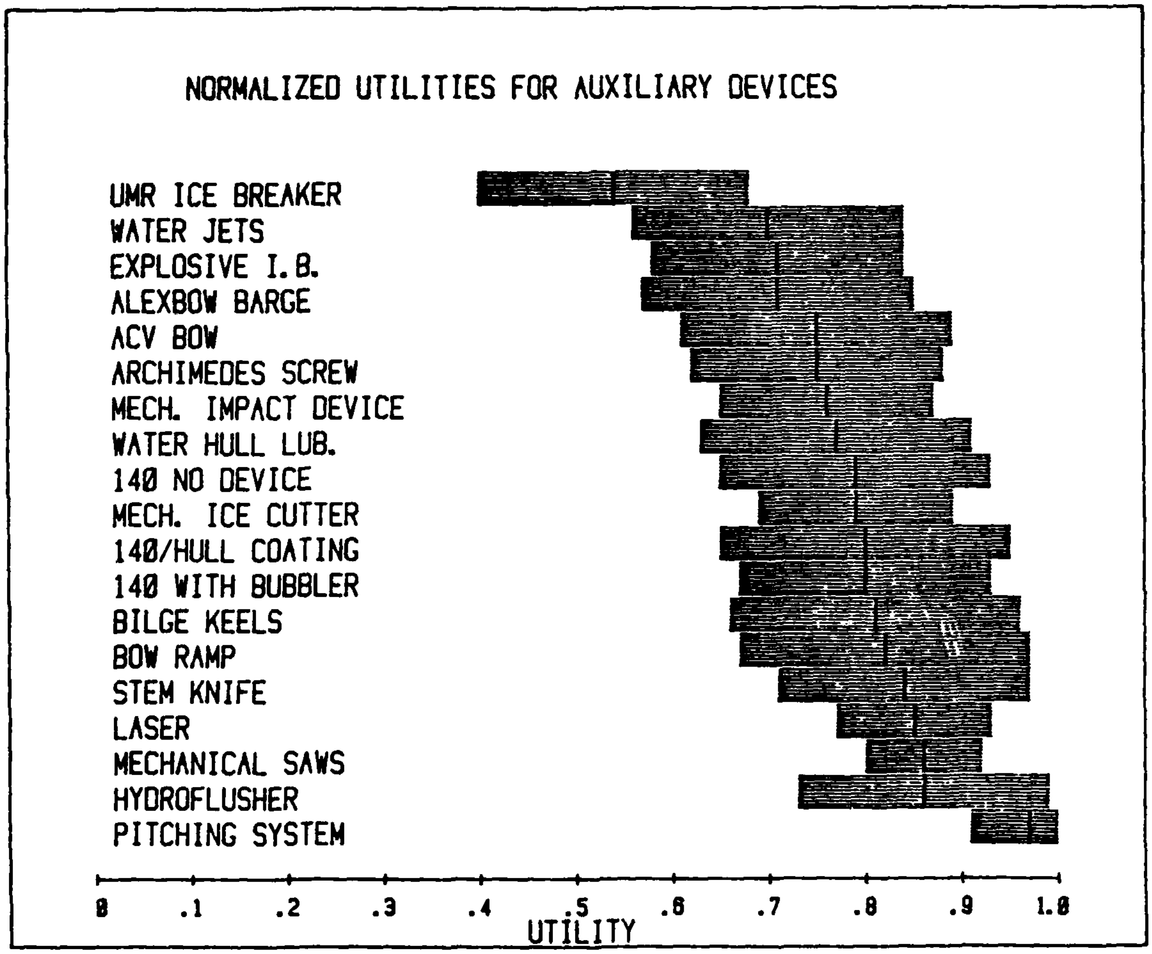

FIGURE 3-1

AVERAGE UTILITIES

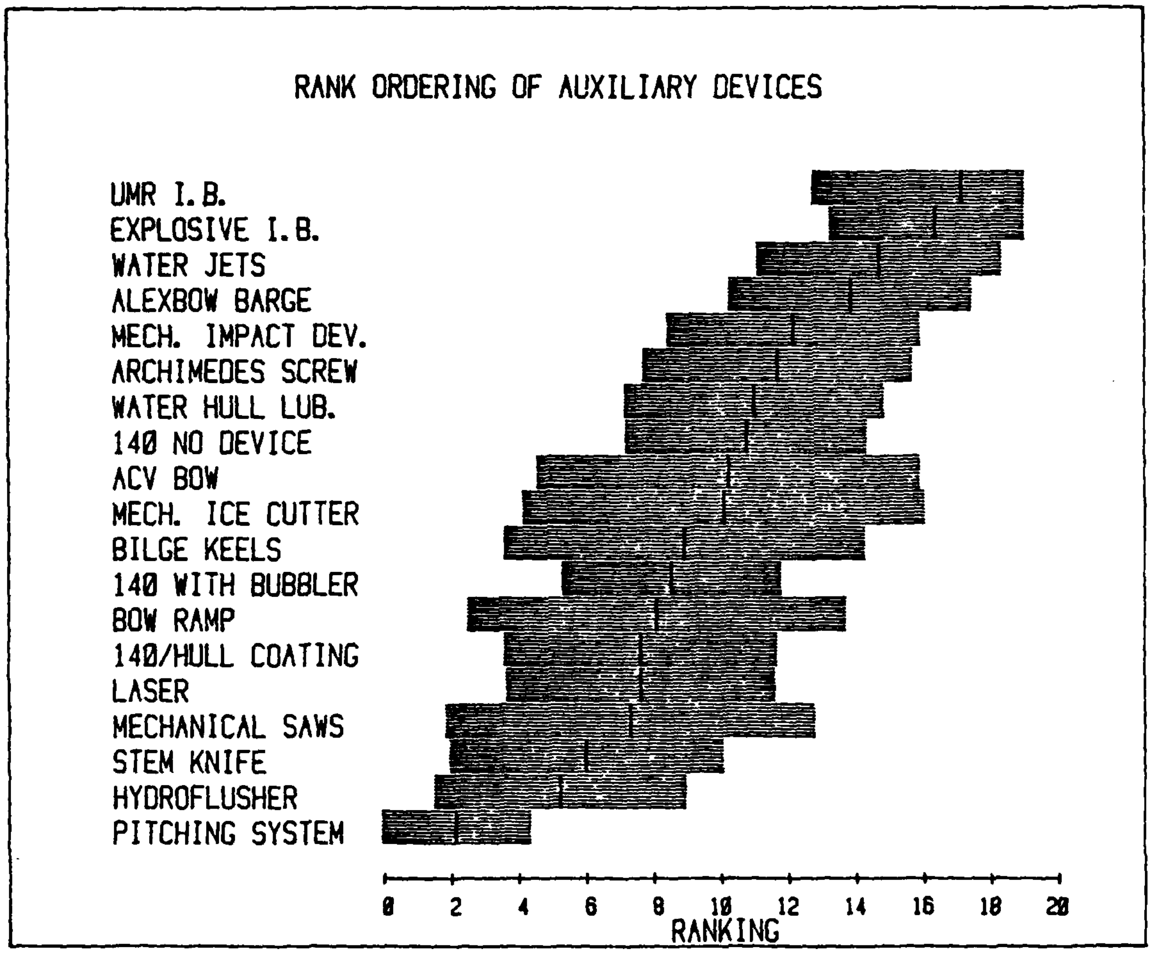

FIGURE 3-2

AVERAGE RANKING

TABLE 3-1
COEFFICIENT OF CONCORDANCE

		PITCHING SYSTEM	MECHANICAL SAWS	MECHANICAL ICECUTTER	LASER	ACV BOW BW	STEM KNIFE	140-BUBBLER	140—HULL COATING	140 NO DEVICES	HYDRO-FLUSHER	BOW RAMP	BILGE KEELS	ALEX BOW BARGE	WATER HULL LUB.	ARCHIMEDES SCREW	MECHANICAL IMPACT DEV.	EXPLOSIVE ICEBREAKER	WATER JETS	UMR ICEBREAKER
WTGB	LT. HEINS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
	LT. NORMAN	2	1	5	3	4	15	12	16	17	6	7	18	19	13	11	9	8	14	10
	LCDR SHERER	1	3	6	4	16	7	9	11	14	2	5	8	12	10	15	13	17	18	19
	LT. EMBLER	1	5	15	10	3	2	7	4	9	11	17	14	18	12	8	13	16	6	19
MACKINAW	LT. BOHAN	1	4	9	8	18	3	5	6	12	2	15	11	17	7	13	10	14	16	19
	CDR ROSEBROOK	1	17	18	8	10	3	11	4	9	6	2	7	13	12	5	16	15	14	19
	CAPT. HALL	7	8	3	10	6	12	14	13	15	4	1	2	9	18	11	17	16	19	5
180'	LT. BURROWS	1	2	3	5	18	7	6	10	13	4	11	12	17	8	16	9	14	15	19
	LT. BELL	1	12	18	3	7	6	9	8	13	2	15	16	17	11	5	4	14	10	19
	LT. YOUNG	2	14	13	17	15	3	9	5	8	6	1	4	7	11	10	12	18	16	19
	CDR PARKS	2	15	18	10	17	9	4	3	8	1	6	7	16	5	11	14	13	12	19
	LCDR MOSHER	1	7	12	10	19	3	5	8	9	2	4	13	11	6	17	15	14	16	18

Table II in Friedman gives values of W that have probabilities of 0.05 and 0.01 when the null hypothesis - significantly lesser degree of agreement than would be expected on the basis of chance - is true. W exceeds the tabled value so we may decide to reject this null hypothesis and conclude that the decisionmakers show a significantly greater degree of agreement than would be expected on the basis of chance.

Furthermore, table 3-1 shows very good agreement in column 1, the Pitching System, and in column 19, the UMR Icebreaker. Considering the wide variance in experience and the fact that no attempt to apply the Delphi method was made, the Pitching System does appear to outrank the other devices quite heavily and deserves a fair amount of further study.

There are many problems associated with group decision-making and there are a multitude of ways in which to attack this problem. (Keeney, Chapter 10.) In this work effort we have assigned equal weights to all the decisionmakers. The analyst may wish to assign weights to individual decisionmakers and/or cluster the decisionmakers in some meaningful way. Care must be taken, however, to use only the ordinal rankings when aggregating individual preferences because, as stated previously, the utilities are unscaled, e.g., one individual's maximum utility for all the devices is .83 while another's is .62. At any rate, obtaining a Group Utility Function is beyond the scope of this effort. Suffice it to say, for this computer exercise, the Pitching System appears to be the most preferred device in most cases based on an ordinal ranking derived from utility estimates.

Tables 1 through 19 in Appendix E show a count of the number of zero utilities found in each attribute/mission function pair for each device. This can give an indication of possible problem areas with respect to a particular attribute. For instance, some fairly large numbers appear across the mission functions for the Maximum Ice Thickness (Ramming) attribute in the table for the Alex Bow Barge. One would expect this device to operate poorly in this mode. Conversely, very few numbers appear for Ice Displacement which indicates no serious problems would be expected in displacing ice for this device. This type of analysis does not pick out areas in which the device is expected to be highly preferred. The printouts in Volume 2 should be analyzed for highly preferred attributes. As previously mentioned, these zeros are the result of the density function being placed sufficiently below the thresholds of the utility function. Therefore, this is engineering judgement and does not reflect the decisionmaker's preference, i.e., one cannot infer from the fact that no zero's exist in a row that high utilities exist for the corresponding attribute. This must be derived from the computer printouts.

Decision models are not exact and are subject to many types of errors including judgemental, computational and omission of intangibles such as the ability to predict future individual preferences once an alternative has been implemented. Sensitivity Analysis is performed in order to somewhat cut down on these problems, i.e., to increase our confidence in the selection procedure. By changing some critical parameters and noting the outcomes, we can assure ourselves that the final ranking would or would not be significantly affected if we were slightly incorrect in estimating the utilities.

Although an extensive, all inclusive set of sensitivity runs could not be accomplished in the time frame allowed, some runs were made changing a few of the critical attributes such as Speed and no significant changes were observed in the four or five top device rankings.

Appendix G describes an automatic sensitivity analysis performed by the computer program. Complete results of this analysis for the top seven devices appear after the listing of the rankings for each decisionmaker's printout. The mathematics that were used to produce the matrix of numbers is described in Appendix G. Each attribute had been varied (perturbed) by the deviation factor shown in the left-most column of the printout. This deviation factor was input into a statistical formula given in Appendix G and the program essentially changes each attribute according to the appropriate value of the deviation factor. The result given for each deviation factor/attribute pair is the expected utility that the device would have if that attribute were perturbed by the given amount.

The perturbed utilities increase from a deviation factor of 0.10 to 1.50. Therefore, one can think of the perturbations at the 0.10 level as the lower bound and the values at the 1.50 level as the upper bound for expected utility of the device when perturbed + 90% of its nominal value, i.e., expected utility given in the ranked list. It would be at a deviation factor of 100 and remain the same for all attributes in the row. Note the nominal value is not shown in the printouts.

Looking down a column of perturbed utilities under a particular attribute the analyst can detect the sensitivity of that attribute in computing the overall utility, i.e., how much of a role that attribute played in determining the preference rating of the device.

Furthermore, one can look at differences in utility contribution between alternatives. By noting the minimum and maximum values obtained by the analysis, one can see how much overlap occurs for each attribute as we change alternatives, i.e., no overlap implied the optimum alternative's attribute, say Speed, was clearly superior, while some overlap indicates uncertainty as to whether the attribute may have been superior for the higher ranking alternative.

4.0 CONCLUSIONS

This study represented the first comprehensive evaluation and ranking of all the auxiliary icebreaking devices which have been proposed over the last fifty years. An extensive literature search and many interviews with experienced personnel produced a list of 19 alternatives to evaluate. A set of quantifiable attributes were selected so that operational personnel would be able to relate their icebreaking experiences to a wide range of numerical values of the attribute while operating in a particular mission environment. Decision Analysis was used to provide a measure of the interrelationships between the factors involved in icebreaking.

A computer model was developed in order to assimilate all of the information into a logical structure. Operational experience and engineering judgement provided the inputs to the model in the form of lotteries and probability densities. The model produced a rank order for the 19 alternatives based on their utility in meeting the goals and objectives of the Coast Guard.

The results of this study indicate that there is little practical difference between any of the auxiliary devices when all the factors involved are considered. Only one system was clearly superior to the others. This was the Pitching System in which a set of rotating weights are used to induce a pitching motion to the hull while icebreaking. This is a well proven system which has been used in Germany for many years. However, the cost of retrofitting existing Coast Guard vessels would be high. A further study of the application of Pitching Systems to Coast Guard vessels is recommended.

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APPENDIX A

DRAWINGS OF ALTERNATIVES

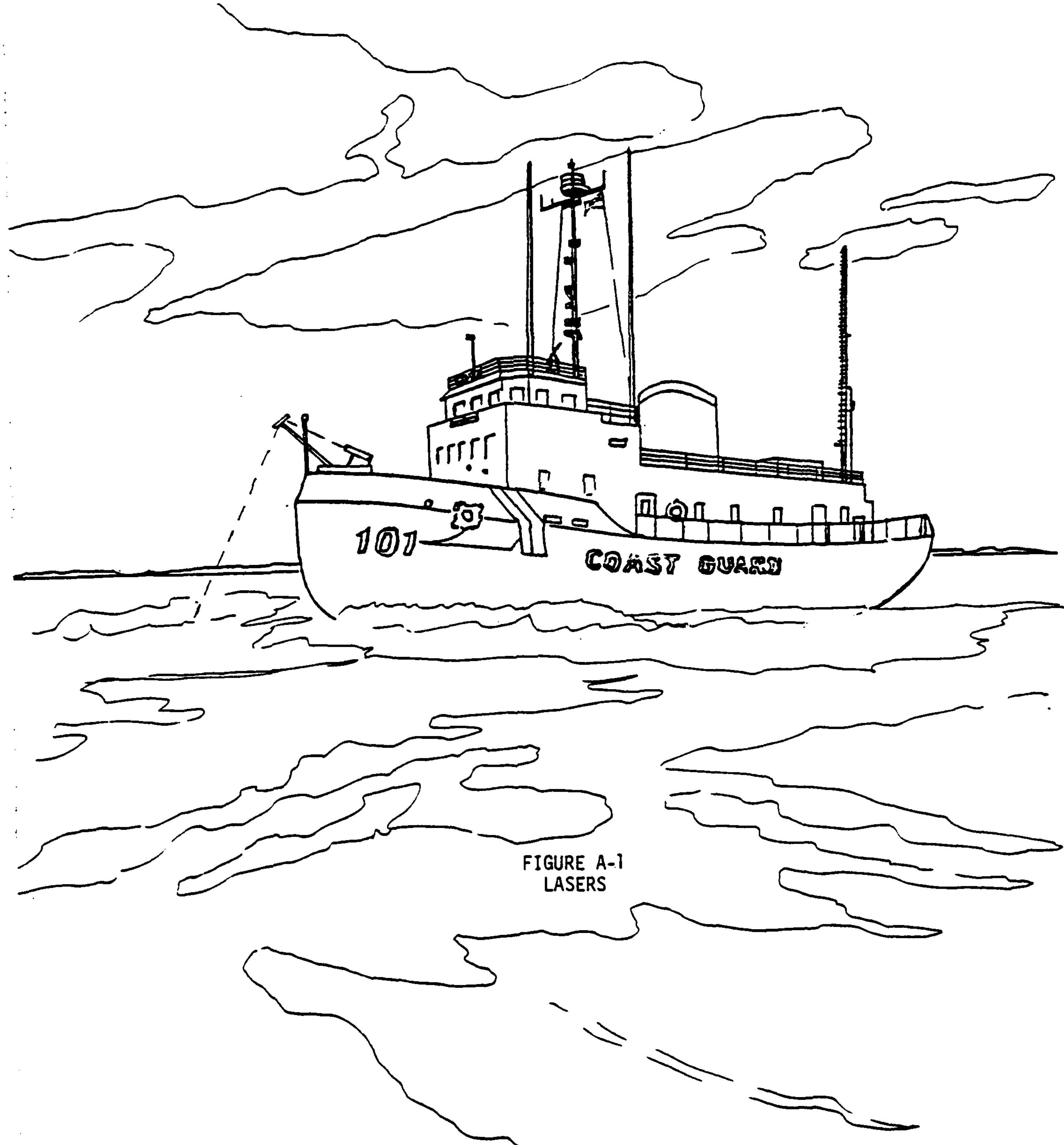


FIGURE A-1
LASERS

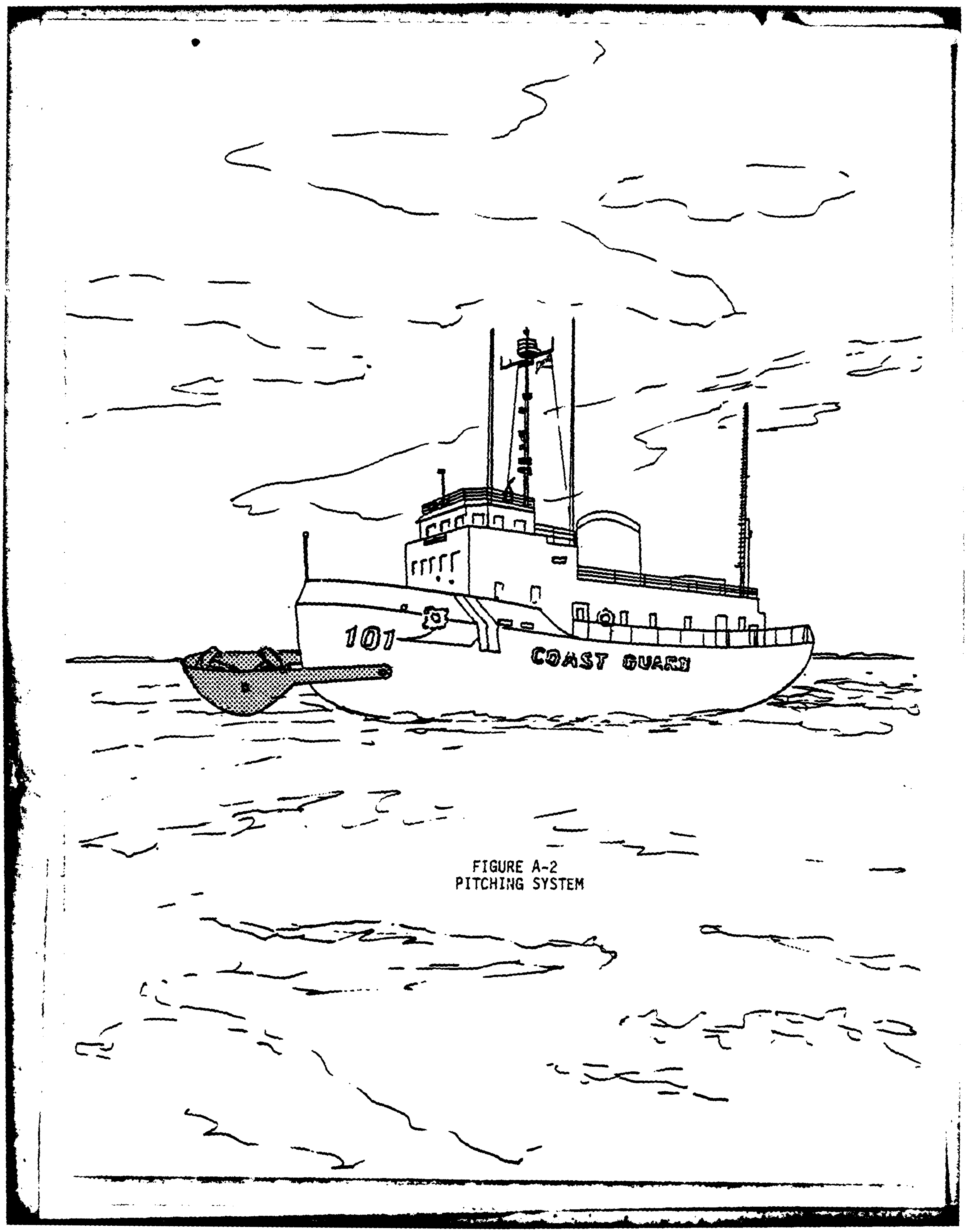


FIGURE A-2
PITCHING SYSTEM

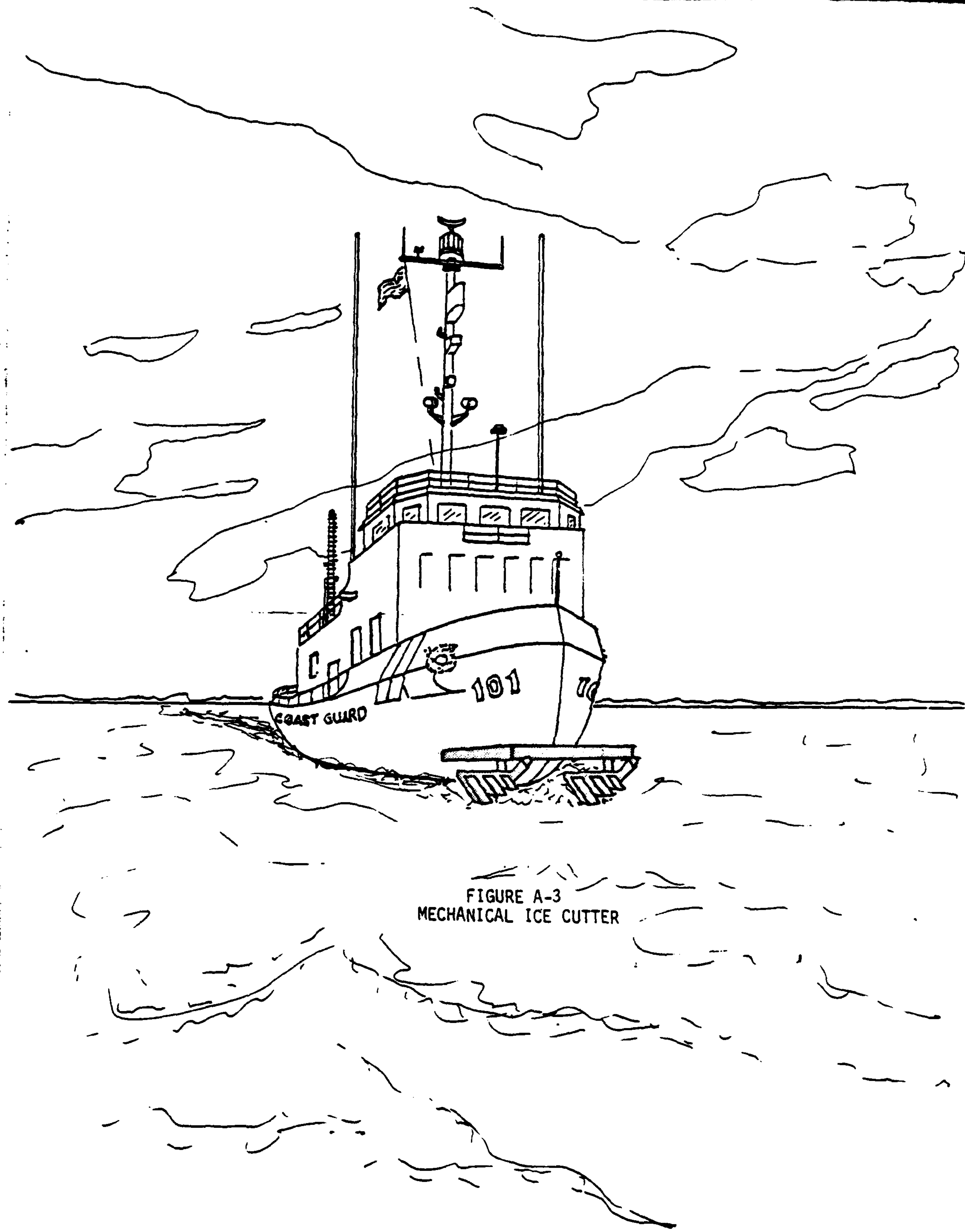


FIGURE A-3
MECHANICAL ICE CUTTER

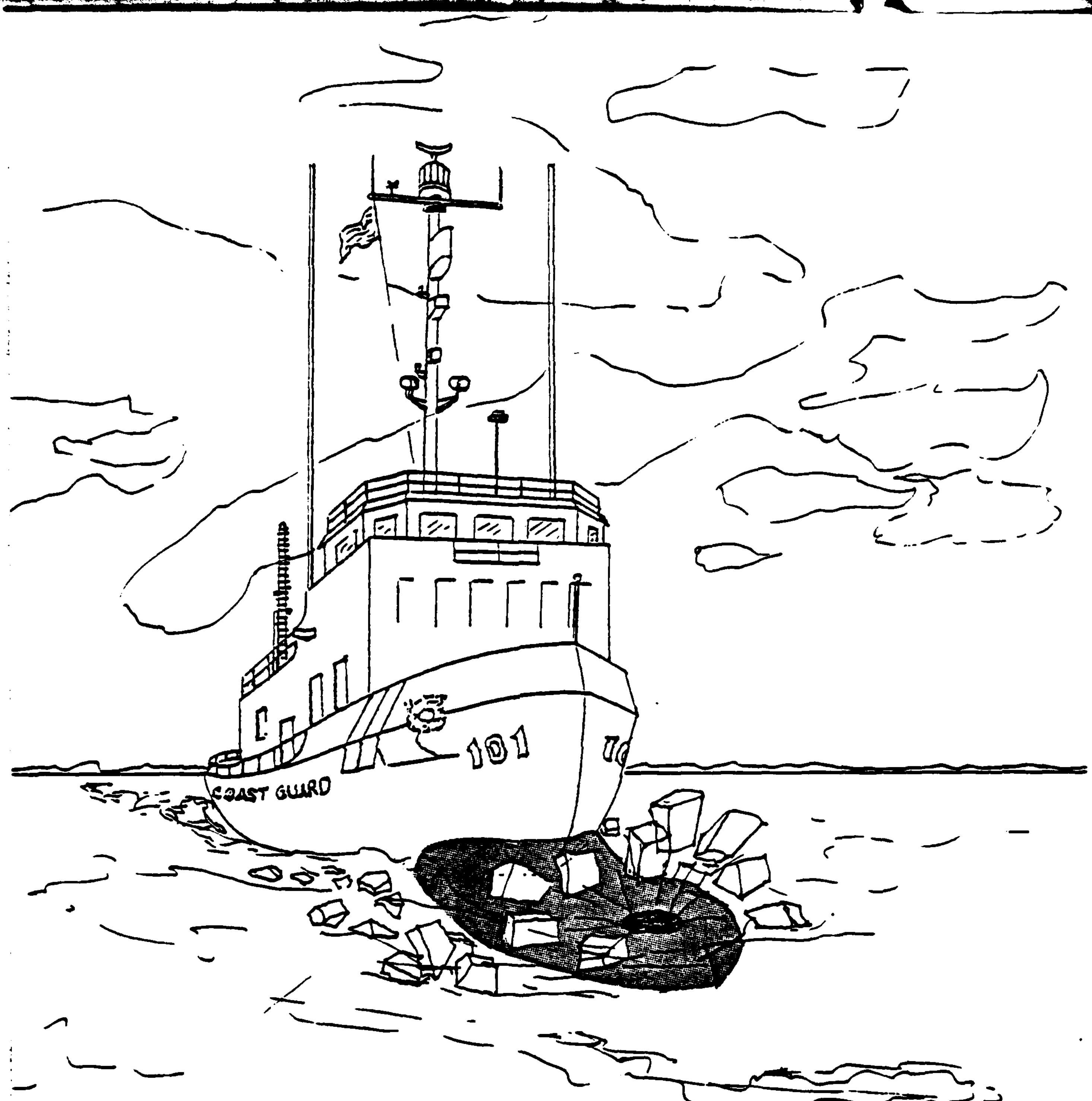


FIGURE A-4
EXPLOSIVE ICEBREAKER

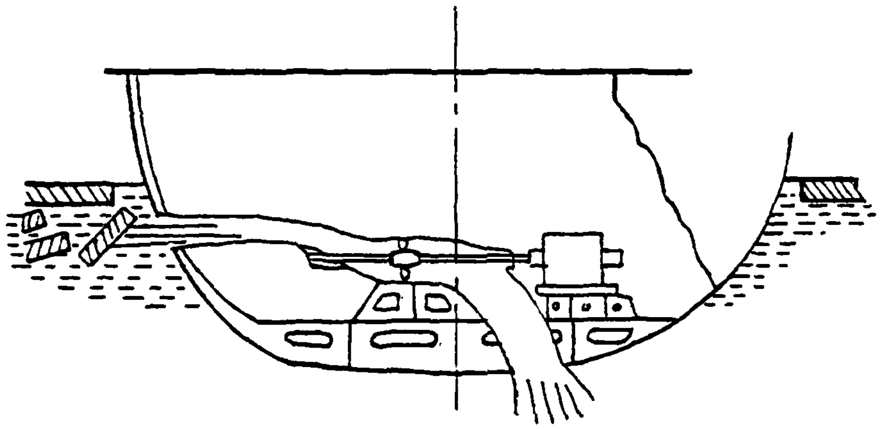


FIGURE A-5
HYDROFLUSHER

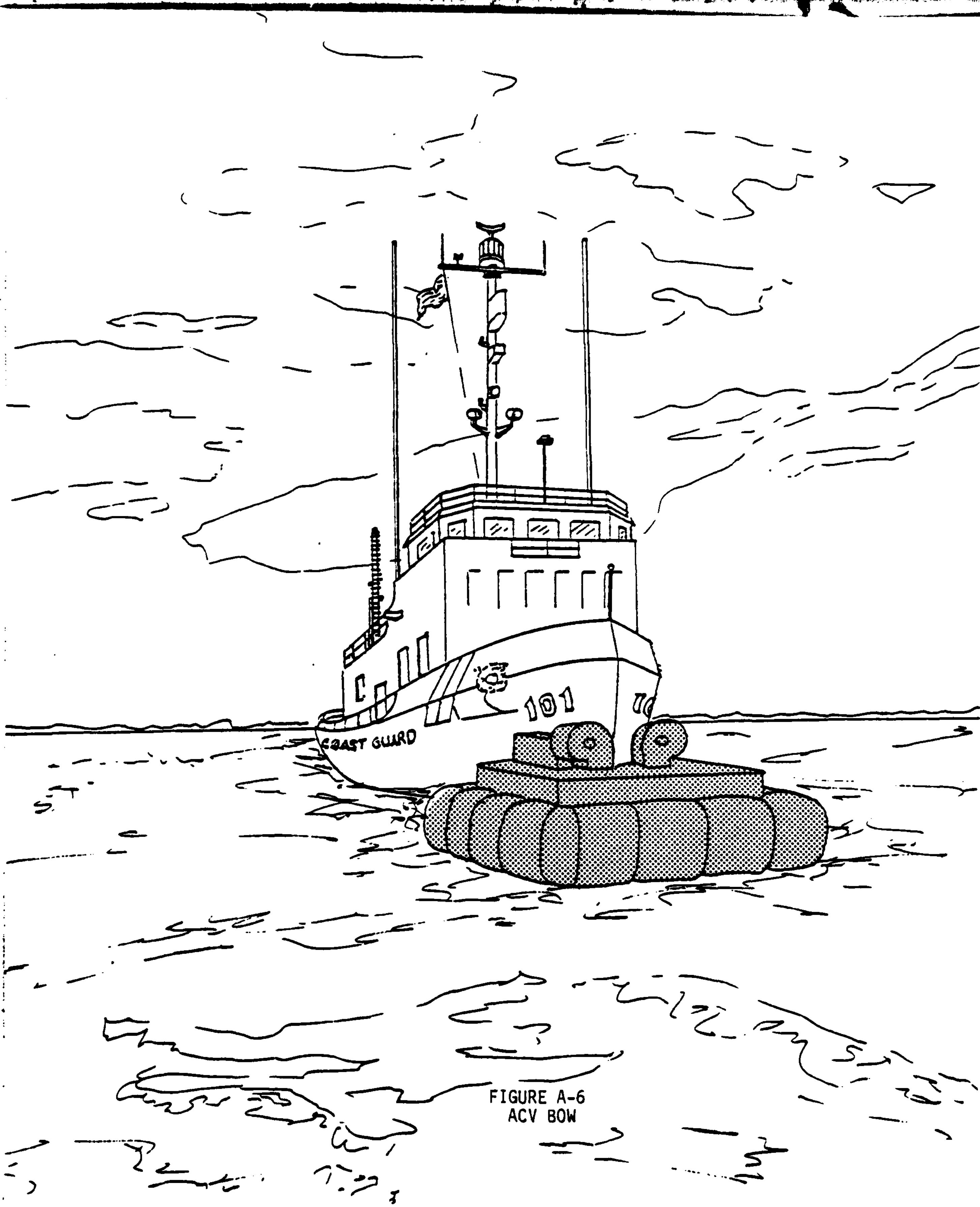


FIGURE A-6
ACV BOW

FIGURE A-7
UPPER MISSISSIPPI ICEBREAKER

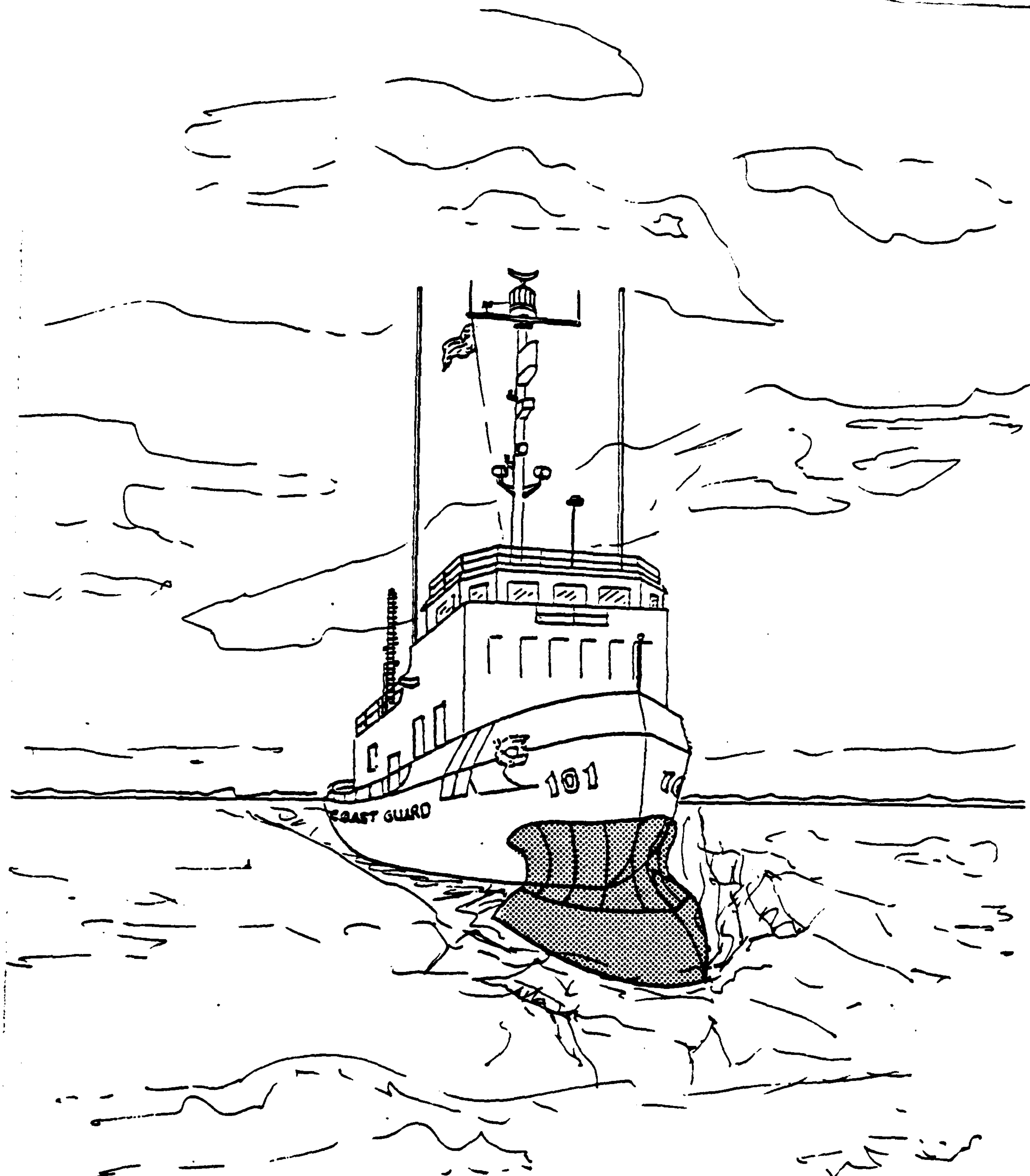


FIGURE A-8
ALEX BOW BARGE

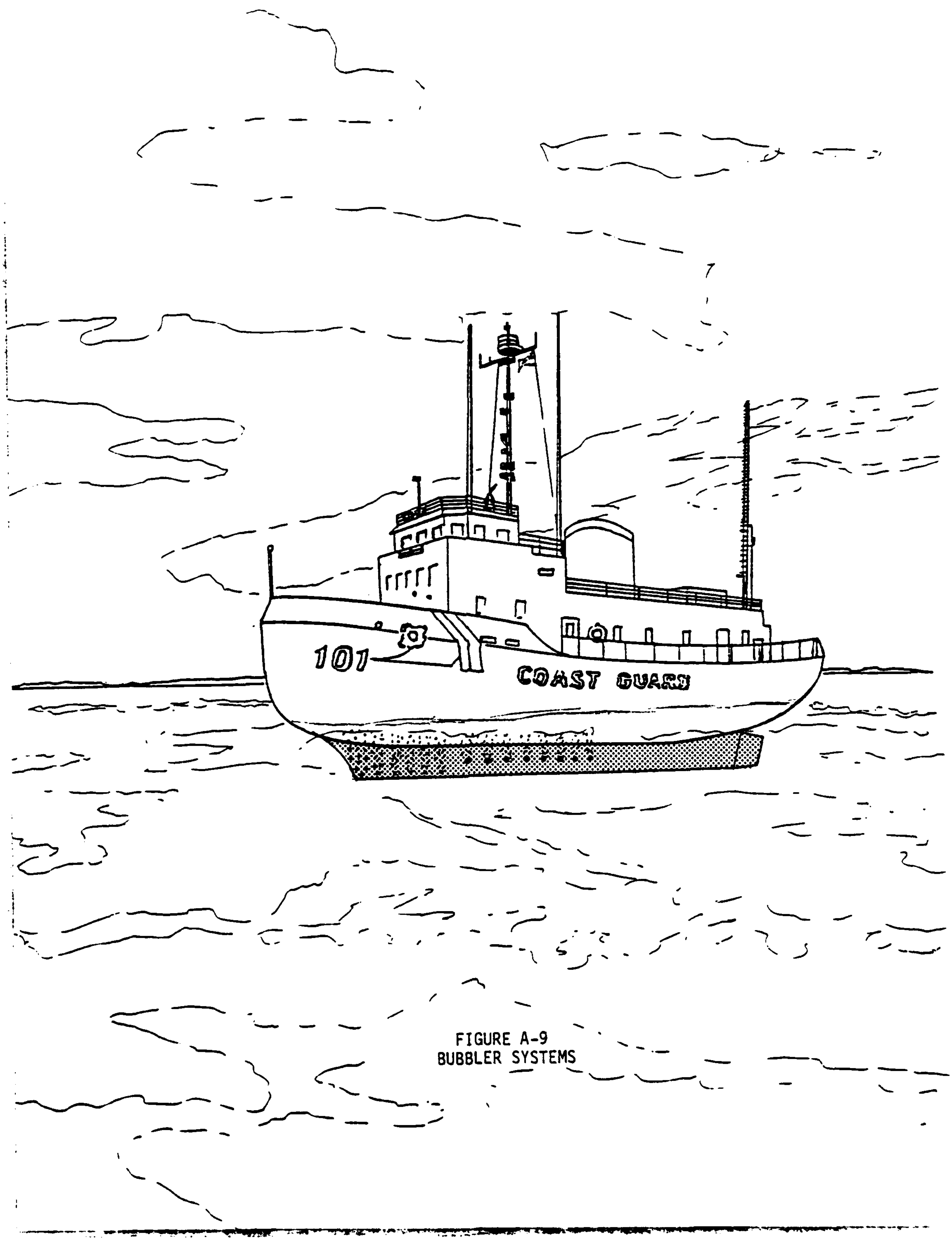


FIGURE A-9
BUBBLER SYSTEMS

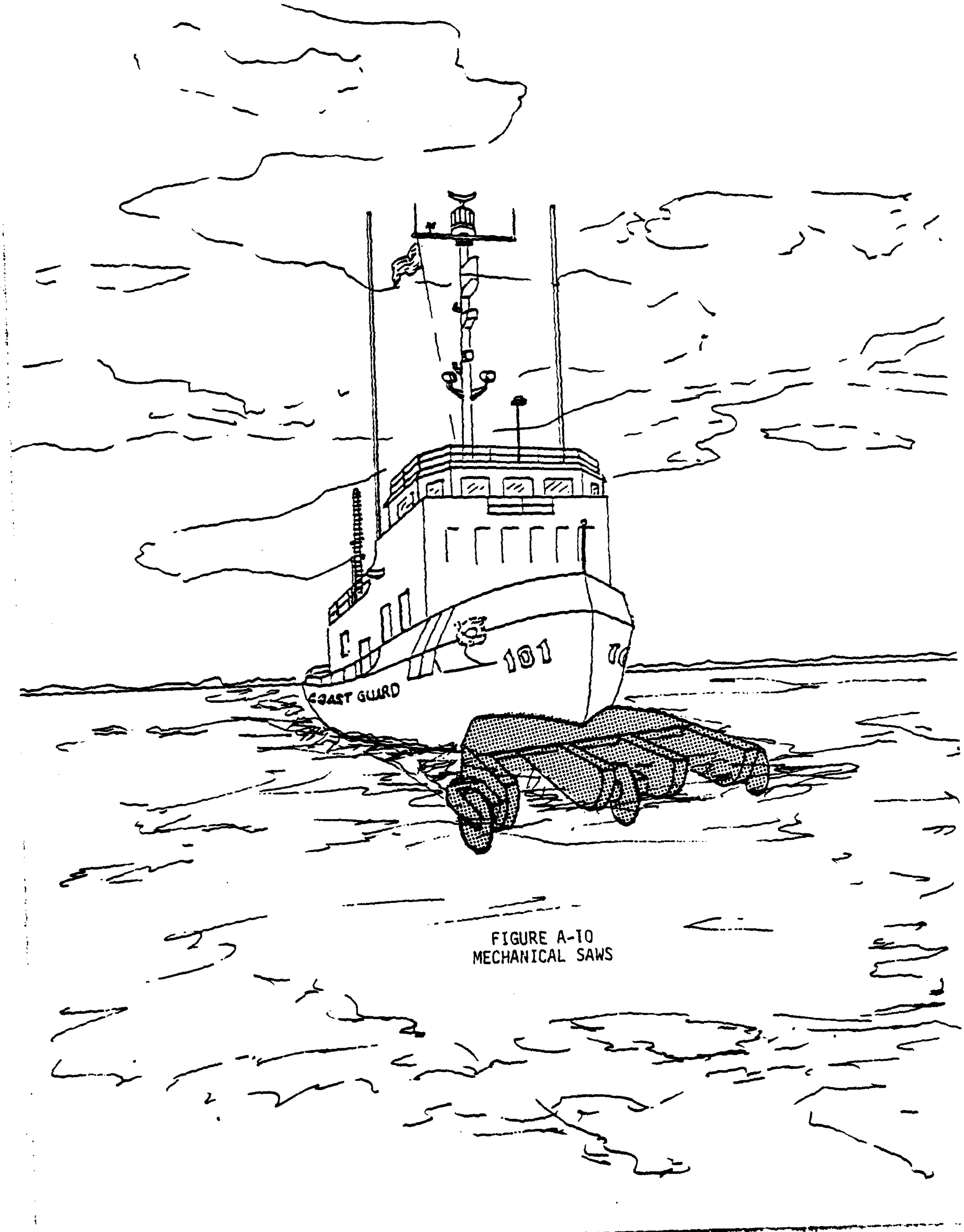


FIGURE A-10
MECHANICAL SAWS

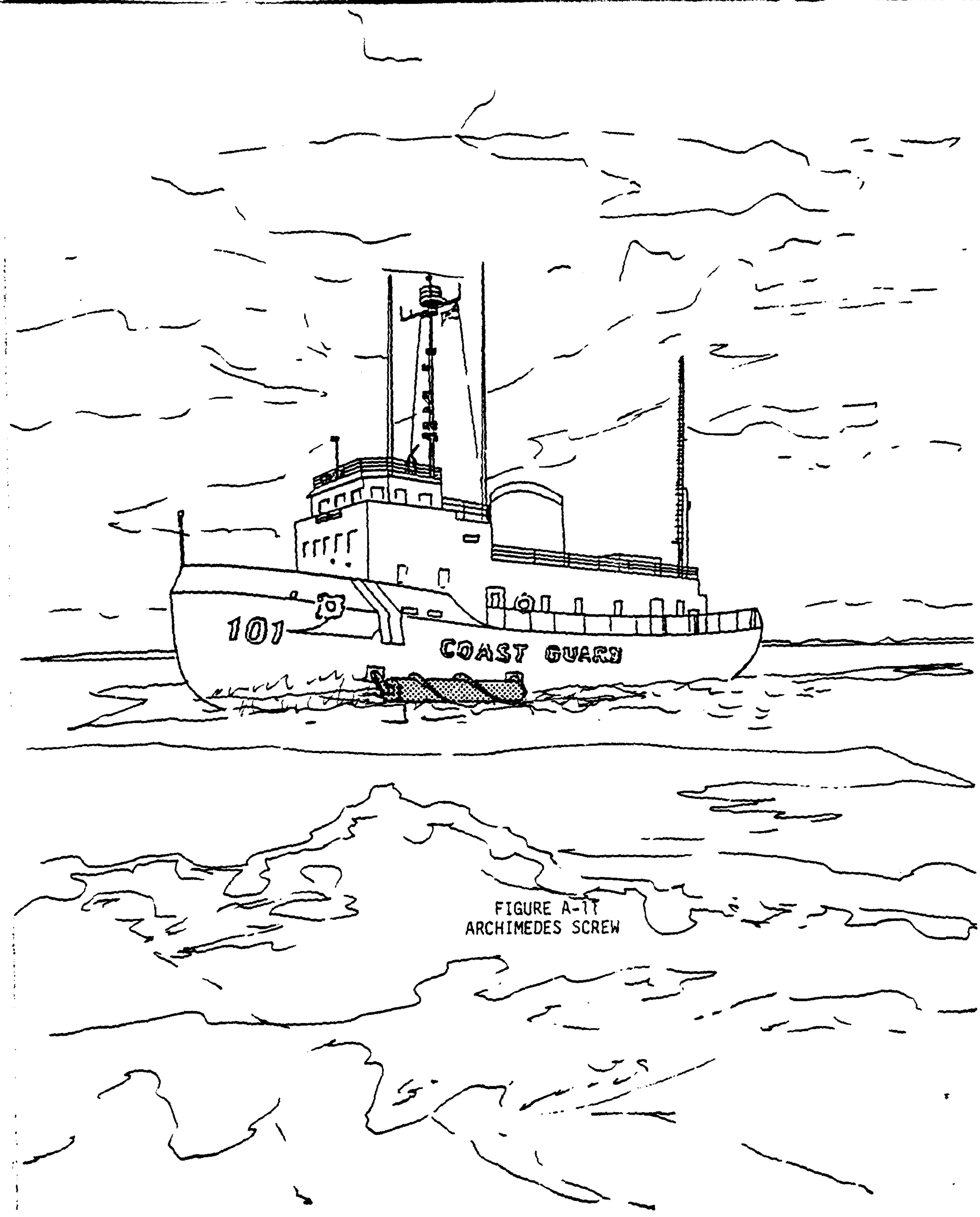


FIGURE A-11
ARCHIMEDES SCREW

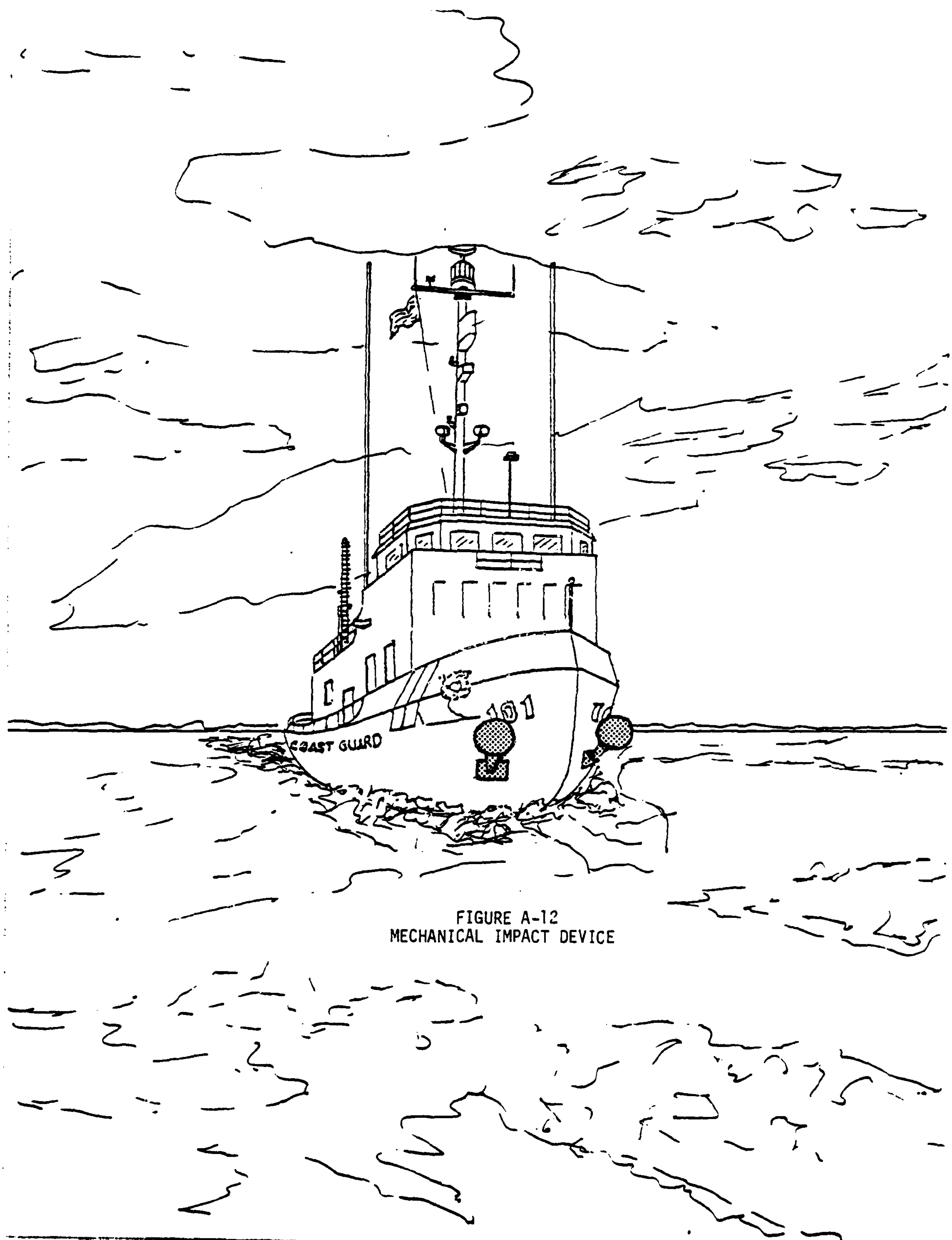


FIGURE A-12
MECHANICAL IMPACT DEVICE

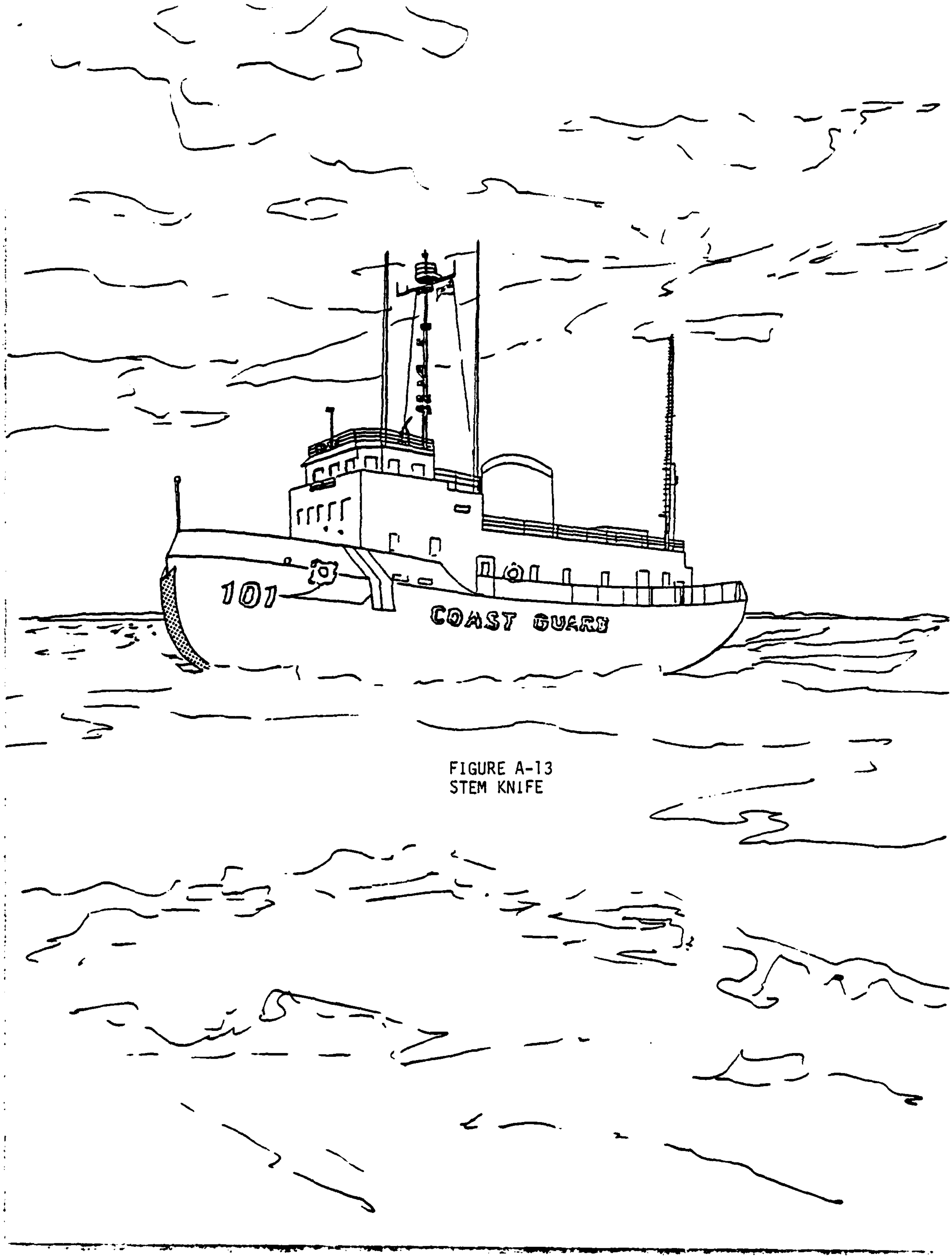


FIGURE A-13
STEM KNIFE

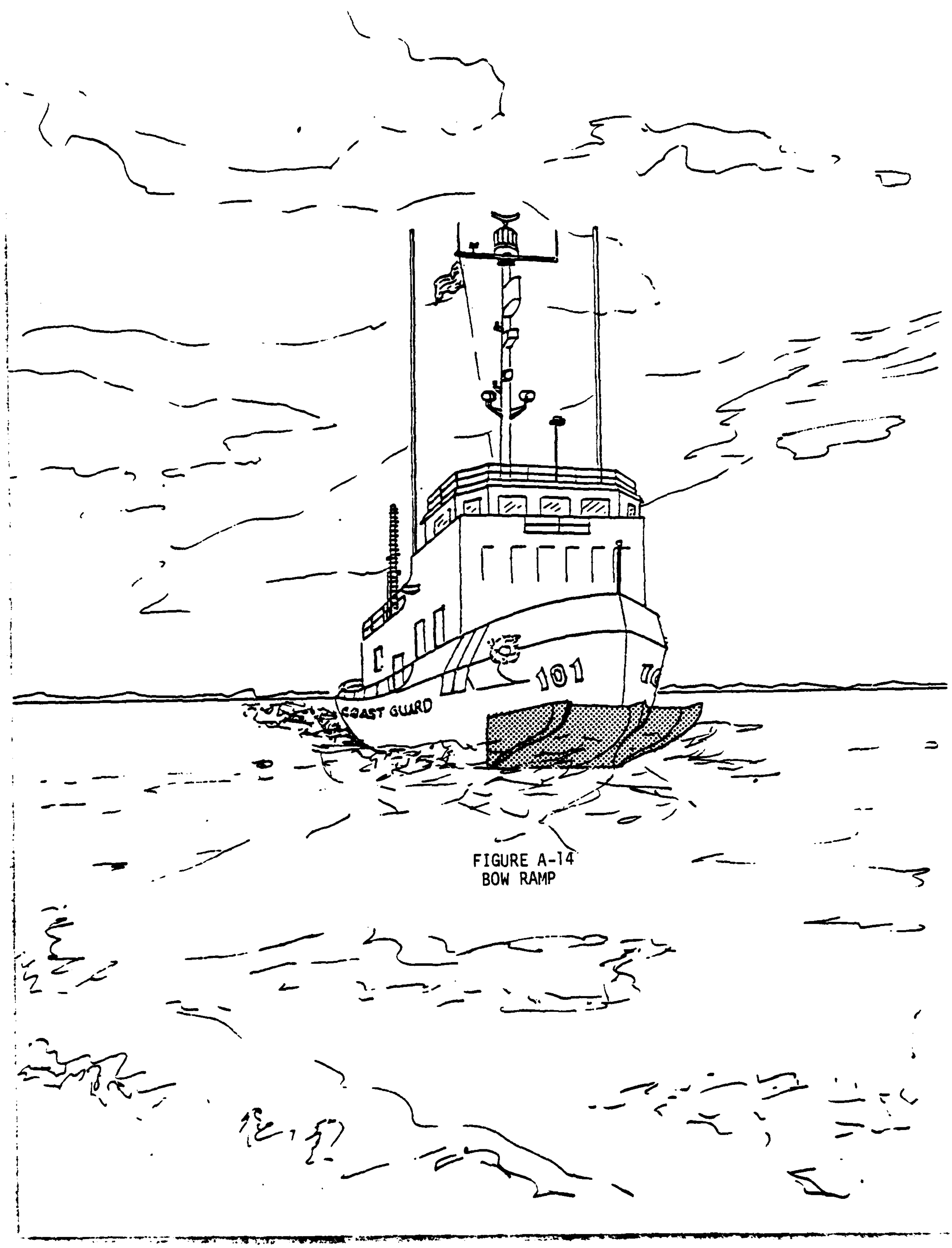


FIGURE A-14
BOW RAMP

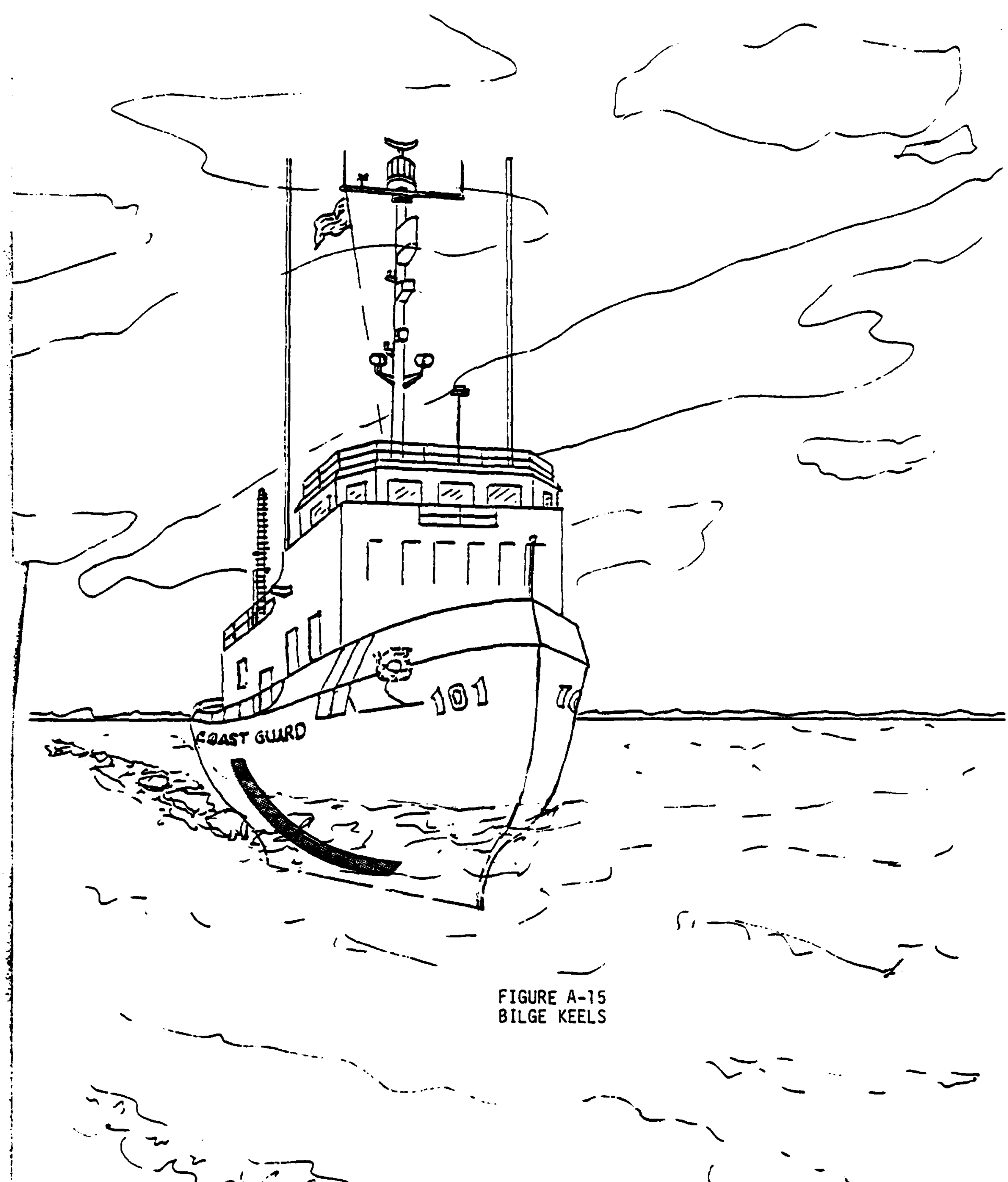


FIGURE A-15
BILGE KEELS

APPENDIX B

APPENDIX B

AXIOMS OF UTILITY AND THE DERIVATION OF THE CONCEPT OF A LOTTERY

For the purpose of the following derivation, the elements of the decision situation are defined as follows:

1. There is a finite set of mutually exclusive and exhaustive basic prizes denoted by

$$H = (h_1, h_2, \ldots, h_j, \ldots, h_n) \tag{B-1}$$

These prizes are, in principal, perfectly general; they might include an automobile, a boat, a trip to Europe, various configurations of an icebreaker, or sums of money.

2. There is a set of probabilities

$$P = (p_1, p_2, \ldots, p_j, \ldots, p_n) \tag{B-2}$$

such that h_1 can be won with probability p_1, h_2 can be won with probability p_j. In addition, since the members of H are mutually exclusive and exhaustive, the following relationships hold:

$$\sum_j p_j = 1 \tag{B-3}$$

$$P(h_i+h_j) = p_i + p_j \text{ for all } i = j \tag{B-4}$$

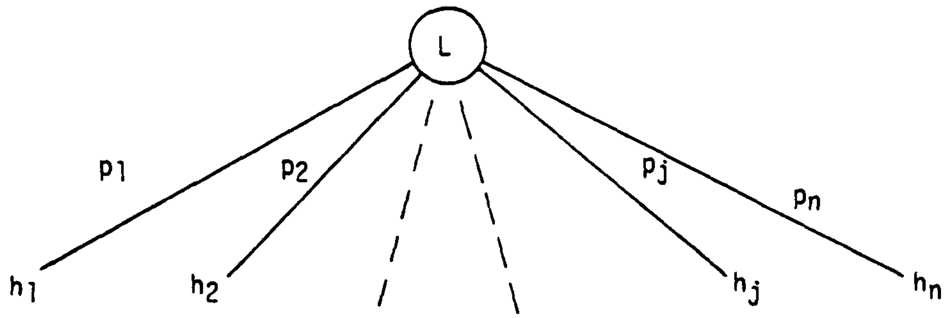
where $P(h_i+h_j)$ = probability of h_i or h_j

$P(h_j)$ may be determined by throwing honest dice or by selecting numbered balls at random (as in the game of Bingo).

3. A lottery, L, is a chance mechanism which yields H with the known probabilities P. One and only one h_j will be won and the probability that it will be won is p_j. The lottery L is represented by

$$L = (h_1p_1, h_2p_2, \ldots, h_jp_j, \ldots, h_np_n) \tag{B-5}$$

The meaning of L may be clarified by the following tree diagram:



The tree diagram portrays the mutually exclusive events (or "paths") which may occur, the probability associated with each path and the prize associated with each path.

"h_j is not preferred to h_i" is denoted by

$$h_i \succsim h_j; \qquad (B\text{-}6)$$

"h_i is preferred to h_j" is denoted by

$$h_i \succsim h_j; \qquad (B\text{-}7)$$

"h_i is equivalent to h_j" is denoted by

$$h_i \sim h_j; \qquad (B\text{-}8)$$

It is assumed that the decisionmaker knows the sets H and P and furthermore, behaves in accordance with the following assumptions:

AXIOM 1 Comparability. The decisionmaker has either preference or indifference for any h_j with respect to any other member of H. The decisionmaker is willing to compare any prize h_j with any other prize which is a member of H, and he can determine which of the preference relationships applies.

AXIOM 2 Transitivity. If $h_i \succ h_j$ and $h_j \succ h_k$, then $h_i \succ h_k$. Also when considering a set of lotteries, if $L_i \succ L_j$ and $L_j \succ L_k$, then $L_i \succ L_k$.

AXIOM 3 Compound Lotteries. Any compound lottery can be reduced to an equivalent simple lottery by operating with the probabilities according to the rules of the probability calculus. Consistency requires that the decisionmaker behave according to this axiom.

AXIOM 4 Continuity. In comparing h_j, any member of H, with a lottery l_j involving the best prize h_1, and the worse prize h_n, there exists a probability u_j such that the decisionmaker is indifferent between h_j and the lottery; there is a probability u_i such that:

$$h_j \sim (u_j\, h_1,\ (1-u_j)\, h_n) = l_j \qquad (B\text{-}9)$$

AXIOM 5 Substitutability. In any lottery l_j may be substituted for h The indifference between h_j and l_j is assumed to be unaffecte by other prizes in a lottery in which h_j is a prize.

AXIOM 6 Monotinicity. Lottery $(ph_1, (1-p)\ h_n) \succsim$ Lottery $(qh_1, (1-q)\ h_n)$ if and only if $p \geqq q$.

This appears reasonable. Between two lotteries involving only the most and least desirable prizes, the decisionmaker should prefer the lottery in which the most desirable prize is more probable.

This axiom provides the basis for deciding between two lotteries L, with probabilities P and L_2 with probabilities Q. By the first 5 axioms, L_1 and L_2 may be reduced to the form of the lotteries in Axiom 6 and the decision is made on the basis of whether $p > q$ or $q > p$ where

$$p = \sum p_j\ u_j \tag{B-10}$$

$$q = \sum q_j\ u_j \tag{B-11}$$

The quantity $p = \sum p_j\ u_j$ provides a measure of the decisionmaker's relative preferences for various lotteries. But $\sum p_j\ u_j$ is, by definition, the expected (or arithmetic mean) value of u which is associated with lottery L_r:

$$E(u)_r = \sum p_{jr}\ u_j \tag{B-12}$$

where $E(u)_r$ = expected u associated with lottery L_r

p_{jr} = probability associated with u_j and L_r

If the decisionmaker accepts the preceeding six axioms and if he is rational, then, in choosing among lotteries, in making decision under risk, the decisionmaker should choose that alternative for which E(u) is greatest.

As a result of the foregoing discussion, we may state the following concerning u_j.

a. u_j is identified by the decisionmaker as the probability which makes the following relationship from Axiom 4 true for each h_j.

$$h_j \sim (u_j h_1,\ (1-u_j)\ h_n) = l_j \tag{B-13}$$

b. The magnitude of u_j depends on the decisionmaker's preference for h_j, the greater his preference, the larger is u_j. For example, $u_1 = 1.0$ for h_1, the most preferred prize, and $u_n = 0$ for h_n; the least preferred prize. For each intermediate prize, the magnitude of u_j will be between 0 and 1, and the greater the decisionmaker's preference for h_j, the greater the magnitudes of u_j (Axiom 6).

c. The numbers which the decisionmaker assigns for each u_j, although defined as a probability, measures the decisionmakers preferences for each h_j on a cardinal scale, for

$$u_i > u_j \text{ if and only if}$$

$$h_i \succ h_j$$

and, in comparing lotteries

$$E(u)_r > E(u)_s \text{ if and only if}$$

$$L_r \succeq L_s$$

If $u(h_j)$ is defined as the utility of h_j, then $u(h_j) = u_j$.

The set of (u_j) provides, therefore, a cardinal measure of utility over H and $E(u)_r$ is the expected utility associated with lottery L_r.

The axioms provide a rational decision rule; MAXIMIZE EXPECTED UTILITY, and making a decision in accordance with this rule means that the decision will be consistent with the preferences expressed by the decisionmaker in the formulation of the utility scale.

APPENDIX C

APPENDIX C

Method for Assigning Relative Weights to Attributes

Let C_1, C_2, ..., C_n be the set of attributes to be weighted (scaled). Quantiful judgements on pairs of attributes C_i, C_j can be represented by an n-by-n matrix:

$$A = (a_{ij}) \qquad (i,j = 1, 2, \ldots, n) \qquad \text{(C-1)}$$

The entries a_{ij} are defined by the following

Condition 1. If $a_{ij} = x$, then $a_{ij} = 1/x$, $x = 0$

Condition 2. If C_i is judged to be of equal relative importance as C_j, then $a_{ij} = 1$, $a_{ji} = 1$; $a_{ii} = 1$ for all i.

The matrix A has the form

$$A = \begin{bmatrix} 1 & a_{12} & \ldots & a_{1n} \\ 1/a_{12} & 1 & \ldots & a_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots \\ 1/a_{1n} & 1/a_{2n} & \ldots & 1 \end{bmatrix} \qquad \text{(C-2)}$$

Having recorded the quantified judgements on pairs (C_i, C_j) as *numerical* entries a_{ij} in matrix A, the problem is to assign to the n attributes, C_1, C_2, ..., C_n a set of numerical weights w_1, w_2, ..., w_n that would reflect the recorded judgements.

Assume that the "judgements" are the result of precise physical measurements. The judges are given a set of stones, C_1, C_2 ..., C_n and a precision scale. To compare C_1 with C_2, C_1 is put on a scale and its weight, w_1, is 305 pounds. C_2 is weighed and its weight, w_2 is 244 pounds. Divide w_1 by w_2 and get 1.25. The judgement in this case is, " C_1 is 1.25 times as heavy as C_2". ($a_{12} = 1.25$). Therefore, in the case of exact measurement, the relations between the weights w_i and the judgements a_{ij} are given by

$$\frac{w_i}{w_j} = a_{ij} \text{ (for } i, j = 1, 2, \ldots, n) \qquad \text{(C-3)}$$

and

$$A = \begin{bmatrix} w_1/w_1 & w_1/w_2 & \ldots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \ldots & w_2/w_n \\ \ldots & \ldots & \ldots & \ldots \\ w_n/w_1 & w_n/w_2 & \ldots & w_n/w_n \end{bmatrix} \qquad \text{(C-4)}$$

Since physical measurements are never exact in a mathematical sense, allowance must be made for deviations. Moreover, these deviations will be considerably larger in human judgements.

In order to make allowance for deviations, consider the ith row in matrix A. The entries in that row are:

$$a_{i1},\ a_{i2},\ \ldots,\ a_{ij},\ \ldots,\ a_{in} \qquad \text{(C-5)}$$

In the exact case, these values are the same as the ratios:

$$\frac{w_i}{w_1},\ \frac{w_i}{w_2},\ \ldots,\ \frac{w_i}{w_j},\ \ldots,\ \frac{w_i}{w_n} \qquad \text{(C-6)}$$

If the first entry in that row is multiplied by w_1, the second by w_2, and so on, we obtain

$$\frac{w_i}{w_1}\,w_1 = w_i,\quad \frac{w_i}{w_2}\,w_2 = w_i,\ \ldots,\ \frac{w_i}{w_j}\,w_j = w_i,\ \ldots,\ \frac{w_i}{w_n}\,w_n = w_i \qquad \text{(C-7)}$$

The result is a row of identical entries

$$w_i,\ w_i\ \ldots,\ w_i$$

In the general case, (our case), we obtain a row of entries that represent a statistical scattering of values around w_i. It is reasonable, therefore, to require that w_i should equal the average of these values.

or

$$w_i = \frac{1}{n} \sum_{j=1}^{n} a_{ij}\, w_j \quad (i = 1, \ldots, n) \qquad \text{(C-8)}$$

Note, for good estimates, a_{ij} tends to be close to w_i/w_j and is a small perturbation of this ratio. As a_{ij} changes, w_i and w_j change to accomodate the change in a_{ij} from the exact case if n were to also change. Let the value of n be λ. Thus, the problem,

$$w_i = \frac{1}{\lambda} \sum_{j=1}^{n} a_{ij}\, w_j \quad (i = 1, \ldots, n) \qquad \text{(C-9)}$$

has a unique solution. This is the well-known eigenvalue problem.

In general, deviations in the a_{ij} can lead to large deviations both in λ and in w_i, $i = 1 \ldots, n$. However, this is not the case for a reciprocal matrix which satisfies conditions 1 and 2 on page C-1.

If judgement is perfect in all comparisons, $a_{ik} = a_{ij}\, a_{jk}$ for all i, j, k and the matrix A is called consistent.

The matrix equation

$$Ax = y \qquad \text{(C-10)}$$

where $x = (x_1, \ldots, x_n)$ and $y = (y_1, \ldots, y_n)$, is a shorthand notation for the set of equations

$$\sum_{j=1}^{n} a_{ij} \, x_i = y_i \qquad i = 1, \ldots, n \tag{C-11}$$

If comparisons are based on exact measurements, i.e., $w_i, \ldots, w_n$ are already known

$$a_{ij} = \frac{w_i}{w_j} \qquad (i,j, = 1, \ldots, n) \tag{C-12}$$

$$a_{ij} \frac{w_i}{w_j} = 1 \qquad (i,j, = 1, n) \tag{C-13}$$

and

$$\sum_{j=1}^{n} a_{ij} \, w_{ij} \, \frac{1}{w_i} = n \qquad (i = 1, \ldots, n) \tag{C=14}$$

or

$$\sum_{j=1}^{n} a_{ij} \, w_{ij} = n \, w_i \qquad i = 1, \ldots, n \tag{C-15}$$

which is equivalent to

$$A \, w = n \, w \tag{C-16}$$

For matrix theory, this formula expresses the fact that w is an eigenvector of A with eigenvalue n. When written out fully, this equation looks as follows:

$$A = \begin{array}{c|cccc} & A_1 & A_2 & \cdots & A_n \\ \hline A_1 & \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ A_2 & \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ & \vdots & \vdots & & \vdots \\ A_n & \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{array} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = n \begin{bmatrix} w_1 \\ w_2 \\ \\ w_n \end{bmatrix} \tag{C-17}$$

If the a_{ij} are not based on exact measurements, but on subjective judgements, they will deviate from w_i/w_j and equation C-16 will no longer hold. Two results of matrix theory are

(1) If $\lambda_1, \ldots, \lambda_n$ are numbers satisfying the equation

$$Ax = \lambda x \tag{C-18}$$

i.e., are the eigenvalues of A and if $a_{ii} = 1$ for all i, then

$$\sum_{i=1}^{n} \lambda_i = n \tag{C-19}$$

Therefore, if equation 1 holds, all eigenvalues are zero, except one, which is n. In the consistent case, n is the largest eigenvalue of A.

(2) If one changes the entries of a positive reciprocal matrix A by small amounts, then the eigenvalues change by small amounts.

Combining these results, we find that if the diagonal of a matrix A consists of ones ($a_{ii} = 1$), and if A is consistent, then small variations of the a_{ij} keep the largest eigenvalue, λ, close to n, and the remaining eigenvalues close to zero.

Therefore, if A is the matrix of pairwise comparison values, in order to find the "scaling" vector, we must find the vector w which satisfies

$$Aw - \lambda w \tag{C-20}$$

Since it is desirable to have a normalized solution, w is altered by setting

$$z = \sum_{i=1}^{n} w_i \quad \text{and replacing w by (1/2) w.} \tag{C-21}$$

This ensures uniqueness, and also that

$$\sum_{i=1}^{n} w_i = 1 \tag{C-22}$$

Observe that since small changes in a_{ij} imply a small change in λ, the deviation of the latter from n is a measure of consistency. It enables us to evaluate the closeness of our derived scale from an underlying ratio scale which we wish to estimate. Thus, we take

$$\frac{\lambda - n}{n - 1} \tag{C-23}$$

the consistency index, as our indicator of "closeness to consistency." In general, if this number is less than 0.1, we may be satisfied with our judgements.

APPENDIX D

PROBABILITY DENSITY FUNCTIONS - ENGINEER'S JUDGEMENT

TABLE 1
140' WTGB - NO AUXILIARY DEVICES, NO BUBBLERS, NO HULL COATING

ATTRIBUTE	CHANNEL CLEARING			RESPONSE			BREAKOUT			RIVER OPS		
	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX
ICE DISPLACEMENT	5	20	40	5	25	50	5	15	30	0	8	17
MAX THICKNESS RAMMING	25	35	65	25	35	65	25	35	65	25	35	65
MAX THICKNESS CONTINUOUS	17	18.5	21.5	17	18.5	21.5	17	18.5	21.5	17	18.5	21.5
OPEN WATER ACCELERATION	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0
SPEED	10	122	13.5	4.5	6.2	7.5	4.6	6.3	7.8	8.5	10.0	11.7
TRACK WIDTH	38	40	45	38	45	60	38	45	60	38	40	44
MANEUVER-ABILITY	390	480	520	330	390	470	330	390	470	360	450	490
AVAILABILITY	100	100	100	100	100	100	100	100	100	100	100	100
ENDURANCE	277	258	242	114	108	102	184	176	168	196	186	178
FUEL CONSUMPTION	70	75	80	170	180	190	105	110	115	99	104	108
MAINTAIN-ABILITY	0	0	0	0	0	0	0	0	0	0	0	0
ADDITIONAL TRAINING	0	0	0	0	0	0	0	0	0	0	0	0
CARGO CAPACITY	5000	6000	8000	5000	6000	8000	5000	6000	8000	5000	6000	8000
PASSENGER CAPACITY	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 2
HYDROFLUSHER (140' WTGB)

ATTRIBUTE	CHANNEL CLEARING			RESPONSE			BREAKOUT			RIVER OPS		
	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX
ICE DISPLACEMENT	40	70	100	30	60	90	30	60	90	35	65	100
MAX THICKNESS RAMMING	30	40	70	30	40	70	30	40	70	30	40	70
MAX THICKNESS CONTINUOUS	22	24	27	22	24	27	22	24	27	22	24	27
OPEN WATER ACCELERATION	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0
SPEED	12.5	13.6	19.6	8.5	9.7	11.0	8.0	9.4	11.3	9.5	12.0	13.7
TRACK WIDTH	38	40	45	38	45	60	38	45	60	38	40	44
MANEUVER-ABILITY	280	450	520	260	350	470	260	350	470	270	420	490
AVAILABILITY	80	90	95	80	90	95	80	90	95	80	90	95
ENDURANCE	161	155	149	86	82	79	156	150	144	156	150	144
FUEL CONSUMPTION	120	125	130	225	235	245	124	129	134	129	129	134
MAINTAIN-ABILITY	0	0	0	0	0	0	0	0	0	0	0	0
ADDITIONAL TRAINING	.1	.5	1.0	.1	.5	1.0	.1	.5	1.0	.1	.5	1.0
CARGO CAPACITY	2000	3000	5000	2000	3000	5000	2000	3000	5000	2000	3000	5000
PASSENGER CAPACITY	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 3
MECHANICAL IMPACT DEVICES (140' WTGB)

ATTRIBUTE	CHANNEL CLEARING			RESPONSE			BREAKOUT			RIVER OPS		
	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX
ICE DISPLACEMENT	5	20	40	5	25	50	5	15	30	0	8	17
MAX THICKNESS RAMMING	30	50	80	30	50	80	30	50	80	30	50	80
MAX THICKNESS CONTINUOUS	18	24	30	18	24	30	18	24	30	18	24	30
OPEN WATER ACCELERATION	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0
SPEED	11	13	14	6.0	7.5	9.0	6.0	8.0	9.8	9.7	11.0	12.3
TRACK WIDTH	38	40	45	42	55	70	42	55	70	38	40	44
MANEUVER-ABILITY	390	480	520	270	350	430	270	350	430	360	450	480
AVAILABILITY	100	100	100	50	80	90	50	80	90	100	100	100
ENDURANCE	285	265	248	98	94	90	157	150	144	208	198	188
FUEL CONSUMPTION	68	73	78	145	205	215	123	128	133	93	98	103
MAINTAIN-ABILITY	0	0	0	0	0	0	0	0	0	0	0	0
ADDITIONAL TRAINING	4	16	32	[illegible]	16	32	4	16	32	4	16	32
CARGO CAPACITY	4000	5000	7000	4000	5000	7000	4000	5000	7000	4000	5000	7000
PASSENGER CAPACITY	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 4
ALEX BOW BARGE (140' WTGB)

ATTRIBUTE	CHANNEL CLEARING			RESPONSE			BREAKOUT			RIVER		
	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX
ICE DISPLACEMENT	30	60	90	50	80	95	40	70	90	10	25	50
MAX THICKNESS RAMMING	20	30	40	20	30	40	20	30	40	20	30	40
MAX THICKNESS CONTINUOUS	15	18	21	15	18	21	15	18	21	15	18	21
OPEN WATER ACCELERATION	1.6	3.0	4.0	1.6	3.0	4.0	1.6	3.0	4.0	1.6	3.0	4.0
SPEED	5.0	11.0	13.5	3.0	6.0	8.0	3.0	6.5	8.5	5.0	9.0	12.0
TRACK WIDTH	40	50	60	40	55	70	40	55	70	40	50	60
MANEUVER-ABILITY	470	580	620	390	470	565	390	470	565	430	540	590
AVAILABILITY	90	95	100	90	95	100	90	95	100	90	95	100
ENDURANCE	257	242	225	114	108	102	165	159	153	169	162	156
FUEL CONSUMPTION	75	80	85	170	180	190	115	120	125	113	118	124
MAINTAIN-ABILITY	5	10	20	5	10	20	5	10	20	5	10	20
ADDITIONAL TRAINING	0	0	0	0	0	0	0	0	0	0	0	0
CARGO CAPACITY	5000	6000	8000	5000	6000	8000	5000	6000	8000	5000	6000	8000
PASSENGER CAPACITY	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 5
MECHANICAL SAWS AND SCOURING TOOLS (140' WTGB)

ATTRIBUTE	CHANNEL CLEARING			RESPONSE			BREAKOUT			RIVER OPS		
	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX
ICE DISPLACEMENT	5	20	40	10	50	75	10	40	60	0	8	17
MAX THICKNESS RAMMING	30	40	70	30	40	70	30	40	70	30	40	70
MAX THICKNESS CONTINUOUS	24	30	36	24	30	36	24	30	36	24	30	36
OPEN WATER ACCELERATION	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0
SPEED	11	13	14	2.5	3.0	3.5	2.5	3.0	3.5	9.7	11.0	12.3
TRACK WIDTH	38	40	45	45	45	45	45	45	45	38	40	44
MANEUVER-ABILITY	390	480	520	500	700	800	500	700	800	360	450	490
AVAILABILITY	100	100	100	80	90	97	80	90	97	100	100	100
ENDURANCE	285	265	248	84	71	59	116	98	82	208	198	188
FUEL CONSUMPTION	68	73	78	230	270	320	165	195	235	93	98	103
MAINTAIN-ABILITY	0	0	0	0	0	0	0	0	0	0	0	0
ADDITIONAL TRAINING	0	0	0	10	40	80	10	40	80	0	0	0
CARGO CAPACITY	2000	3000	5000	2000	3000	5000	2000	3000	5000	2000	3000	5000
PASSENGER CAPACITY	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 6

140' WTGB WITH HULL COATING; NO AUXILIARY DEVICE; NO BUBBLER

ATTRIBUTE	CHANNEL CLEARING			RESPONSE			BREAKOUT			RIVE		
	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MA.
ICE DISPLACEMENT	5	20	40	5	25	50	5	15	30	0	8	17
MAX THICKNESS RAMMING	30	40	70	30	40	70	30	40	70	30	40	70
MAX THICKNESS CONTINUOUS	18	19	22	18	19	22	18	19	22	18	19	22
OPEN WATER ACCELERATION	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0
SPEED	11	13	14	5.0	6.7	8.2	5.5	7.2	8.7	9.7	11.0	12.3
TRACK WIDTH	38	40	45	38	45	60	38	45	60	38	40	44
MANEUVER-ABILITY	390	480	520	330	390	470	330	390	470	360	450	490
AVAILABILITY	100	100	100	100	100	100	100	100	100	100	100	100
ENDURANCE	285	265	248	114	108	102	198	188	179	208	198	188
FUEL CONSUMPTION	68	73	78	170	180	190	98	103	108	93	98	103
MAINTAIN-ABILITY	0	0	0	0	0	0	0	0	0	0	0	0
ADDITIONAL TRAINING	0	0	0	0	0	0	0	0	0	0	0	0
CARGO CAPACITY	5000	5000	8000	5000	6000	8000	5000	6000	8000	5000	6000	8000
PASSENGER CAPACITY	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 7
ACV BOW (140' WTGB)

ATTRIBUTE	CHANNEL CLEARING			RESPONSE			BREAKOUT			RIVER OPS		
	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX
ICE DISPLACEMENT	5	30	50	10	40	60	10	20	40	0	10	20
MAX THICKNESS RAMMING	30	50	75	30	50	75	30	50	75	30	50	75
MAX THICKNESS CONTINUOUS	25	30	35	25	30	35	25	30	35	25	30	35
OPEN WATER ACCELERATION	2.0	3.3	4.5	2.0	3.3	4.5	2.0	3.3	4.5	2.0	3.3	4.5
SPEED	12	14	14.5	6.0	8.0	9.5	6.2	8.2	9.7	10.3	12.0	13.3
TRACK WIDTH	OPTIMUM			OPTIMUM			OPTIMUM			OPTIMUM		
MANEUVER-ABILITY	390	480	520	330	390	470	330	390	470	360	450	490
AVAILABILITY	20	50	75	20	50	75	20	50	75	20	50	75
ENDURANCE	143	134	125	77	74	72	125	117	111	129	121	114
FUEL CONSUMPTION	135	145	155	250	260	270	155	165	175	150	160	170
MAINTAIN-ABILITY	30	70	90	30	70	90	30	70	90	30	70	90
ADDITIONAL TRAINING	5	10	20	5	10	20	5	10	20	5	10	20
CARGO CAPACITY	20000	26000	30000	20000	26000	30000	20000	26000	30000	20000	26000	30000
PASSENGER CAPACITY	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 8
PITCHING SYSTEM (140' WTGB)

ATTRIBUTE	CHANNEL CLEARING			RESPONSE			BREAKOUT			RIVER OPS		
	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX
ICE DISPLACEMENT	10	30	60	10	30	60	10	20	40	5	15	25
MAX THICKNESS RAMMING	35	60	90	35	60	90	35	60	90	35	60	90
MAX THICKNESS CONTINUOUS	26	33	40	26	33	40	26	33	40	26	33	40
OPEN WATER ACCELERATION	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0
SPEED	11.5	13.5	14.5	9.5	11.0	12.5	10.0	11.5	13.0	10.0	12.0	13.5
TRACK WIDTH	40	42	47	70	80	90	70	80	90	40	42	46
MANEUVER-ABILITY	390	480	520	330	390	470	330	390	470	360	450	490
AVAILABILITY	85	90	95	85	90	95	85	90	95	80	90	95
ENDURANCE	285	265	248	101	94	87	200	190	180	208	198	188
FUEL CONSUMPTION	68	73	78	190	205	220	95	108	105	93	98	103
MAINTAIN-ABILITY	0	0	0	0	0	0	0	0	0	0	0	0
ADDITIONAL TRAINING	0	0	0	0	0	0	0	0	0	0	0	0
CARGO CAPACITY	2000	3000	5000	2000	3000	5000	2000	3000	5000	2000	3000	5000
PASSENGER CAPACITY	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 9
LASERS (140' WTGB)

ATTRIBUTE	CHANNEL CLEARING			RESPONSE			BREAKOUT			RIVER OPS		
	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX
ICE DISPLACEMENT	5	20	40	10	50	75	10	40	60	0	8	17
MAX THICKNESS RAMMING	30	40	70	30	40	70	30	40	70	30	40	70
MAX THICKNESS CONTINUOUS	24	30	36	20	25	28	24	30	36	24	30	36
OPEN WATER ACCELERATION	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0
SPEED	11	13	14	5.5	8.0	10.0	2.5	3.0	3.5	9.7	11.0	12.3
TRACK WIDTH	38	40	45	45	45	45	45	45	45	38	40	44
MANEUVER-ABILITY	390	480	520	330	390	470	330	390	470	360	450	490
AVAILABILITY	100	100	100	70	85	95	70	85	95	100	100	100
ENDURANCE	285	265	248	63	42	36	88	59	48	208	198	188
FUEL CONSUMPTION	68	73	78	300	460	540	220	330	400	93	98	103
MAINTAIN-ABILITY	0	0	0	0	0	0	0	0	0	0	0	0
ADDITIONAL TRAINING	0	0	0	40	80	120	40	80	120	0	0	0
CARGO CAPACITY	2000	3000	5000	2000	3000	5000	2000	3000	5000	2000	3000	5000
PASSENGER CAPACITY	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 10

STEM KNIFE (140' WTGB)

ATTRIBUTE	CHANNEL CLEARING			RESPONSE			BREAKOUT			RIVER OPS		
	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX
ICE DISPLACEMENT	5	20	40	5	25	50	5	15	30	0	8	17
MAX THICKNESS RAMMING	30	45	80	30	45	80	30	45	80	30	45	80
MAX THICKNESS CONTINUOUS	18.5	20	23	18.5	20	23	18.5	20	23	18.5	20	23
OPEN WATER ACCELERATION	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0
SPEED	11	13	14	5.5	7.7	9.5	5.5	8.0	9.7	9.7	11.0	12.3
TRACK WIDTH	38	40	45	38	45	60	38	45	60	38	40	44
MANEUVER-ABILITY	390	500	550	330	410	500	330	410	500	360	460	520
AVAILABILITY	100	100	100	100	100	100	100	100	100	100	100	100
ENDURANCE	297	277	258	113	108	101	225	212	200	237	220	208
FUEL CONSUMPTION	65	70	75	170	180	190	85	90	95	82	87	92
MAINTAIN-ABILITY	0	0	0	0	0	0	0	0	0	0	0	0
ADDITIONAL TRAINING	0	0	0	0	0	0	0	0	0	0	0	0
CARGO CAPACITY	5000	6000	8000	5000	6000	8000	5000	6000	8000	5000	6000	8000
PASSENGER CAPACITY	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 11
WATER JETS/WATER CANNONS (140' WTGB)

ATTRIBUTE	CHANNEL CLEARING			RESPONSE			BREAKOUT			RIVER OPS		
	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX
ICE DISPLACEMENT	5	20	40	5	25	50	5	15	30	0	8	17
MAX THICKNESS RAMMING	42	52	82	42	52	82	42	52	82	42	52	82
MAX THICKNESS CONTINUOUS	19	22	25	19	22	25	19	22	25	19	22	25
OPEN WATER ACCELERATION	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0
SPEED	13.0	13.8	14.3	5.8	7.3	8.0	6.8	7.8	8.5	11.0	12.2	13.0
TRACK WIDTH	38	60	85	38	60	85	38	60	85	38	60	85
MANEUVER-ABILITY	390	480	520	280	350	470	280	350	470	360	450	490
AVAILABILITY	50	80	95	50	80	95	50	80	95	50	80	95
ENDURANCE	117	114	111	72	69	67	108	105	102	111	108	105
FUEL CONSUMPTION	165	170	175	270	280	290	180	185	190	175	180	185
MAINTAIN-ABILITY	0	0	0	0	0	0	0	0	0	0	0	0
ADDITIONAL TRAINING	40	80	120	40	80	120	40	80	120	40	80	120
CARGO CAPACITY	2000	3000	5000	2000	3000	5000	2000	3000	5000	2000	3000	5000
PASSENGER CAPACITY	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 12
800 HP ARCHIMEDES SCREW VEHICLE TUG (140' WTGB)

ATTRIBUTE	CHANNEL CLEARING			RESPONSE			BREAKOUT			RIVER OPS		
	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX
ICE DISPLACEMENT	5	20	50	5	25	50	5	15	30	0	8	17
MAX THICKNESS RAMMING	40	50	80	40	50	80	40	50	80	40	50	80
MAX THICKNESS CONTINUOUS	20	23	25	20	23	25	20	23	25	20	23	25
OPEN WATER ACCELERATION	2.1	2.8	3.5	2.1	2.8	3.5	2.1	2.8	3.5	2.1	2.8	3.5
SPEED	12	14	4.3	7.0	8.1	9.2	7.4	8.5	9.6	11.5	13	14.0
TRACK WIDTH	38	40	45	38	45	60	38	45	60	38	40	44
MANEUVER-ABILITY	350	450	490	290	350	450	290	350	450	320	420	460
AVAILABILITY	70	80	90	70	80	90	70	80	90	70	80	90
ENDURANCE	350	325	295	80	77	74	255	241	226	255	241	226
FUEL CONSUMPTION	55	60	65	240	250	260	75	80	85	75	80	85
MAINTAIN-ABILITY	2	8	16	2	8	16	2	8	16	2	8	16
ADDITIONAL TRAINING	0	4	8	0	4	8	0	4	8	0	4	8
CARGO CAPACITY	10000	12000	16000	10000	12000	16000	10000	12000	16000	10000	12000	16000
PASSENGER CAPACITY	0	0	0	0	0	0	0	0	0	0	0	0

AD-A110 560 COAST GUARD RESEARCH AND DEVELOPMENT CENTER GROTON CT F/G 13/10
COMPARATIVE ANALYSIS OF POTENTIAL AUXILIARY ICEBREAKING DEVICES--ETC(U)
JUN 81 J A SMITH, M J GOODWIN, M S MCBRIDE
UNCLASSIFIED CGR/DC-14/81 USCG-D-33-81 NL

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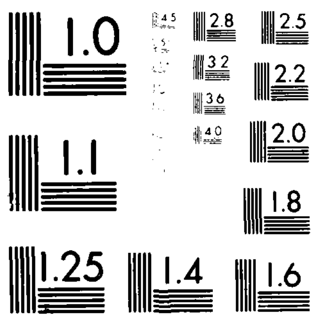


MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

TABLE 13
BOW RAMP (140' WTGB)

ATTRIBUTE	CHANNEL CLEARING			RESPONSE			BREAKOUT			RIVER OPS		
	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX
ICE DISPLACEMENT	60	80	90	70	90	98	70	90	98	0	20	50
MAX THICKNESS RAMMING	20	30	50	20	30	50	20	30	50	20	30	50
MAX THICKNESS CONTINUOUS	20	23	28	20	23	28	20	23	28	20	23	28
OPEN WATER ACCELERATION	1.8	2.7	4.0	1.8	2.7	4.0	1.8	2.7	4.0	1.8	2.7	4.0
SPEED	10	12.5	14	6.0	11.0	13.0	6.0	11.0	13.0	8.0	10.0	11.0
TRACK WIDTH	38	40	45	38	40	45	38	40	45	38	40	45
MANEUVER-ABILITY	390	480	520	330	390	470	330	390	470	360	450	490
AVAILABILITY	90	95	98	90	95	98	90	95	98	90	95	98
ENDURANCE	240	225	213	114	108	102	285	265	248	180	165	153
FUEL CONSUMPTION	80	85	90	170	180	190	68	73	78	105	115	125
MAINTAIN-ABILITY	2	12	25	2	12	25	2	12	25	2	12	25
ADDITIONAL TRAINING	0	0	0	0	0	0	0	0	0	0	0	0
CARGO CAPACITY	5000	6000	8000	5000	6000	8000	5000	6000	8000	5000	6000	8000
PASSENGER CAPACITY	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 14
MECHANICAL ICE CUTTER (140' WTGB)

ATTRIBUTE	CHANNEL CLEARING			RESPONSE			BREAKOUT			RIVER OPS		
	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX
ICE DISPLACEMENT	50	75	90	70	95	100	70	95	100	10	30	60
MAX THICKNESS RAMMING	24	30	36	24	30	36	24	30	36	24	30	36
MAX THICKNESS CONTINUOUS	24	30	36	24	30	36	24	30	36	24	30	36
OPEN WATER ACCELERATION	1.7	2.4	3.2	1.7	2.4	3.2	1.7	2.4	3.2	1.7	2.4	3.2
SPEED	6	9	12	2.5	3.0	3.5	2.5	3.0	3.5	5.0	8.0	10.0
TRACK WIDTH	55	60	65	65	65	65	65	65	65	45	55	65
MANEUVER-ABILITY	500	600	1000	600	1000	1400	600	1000	1400	600	1000	1400
AVAILABILITY	80	90	97	80	90	97	80	90	97	80	90	97
ENDURANCE	225	213	200	84	71	59	116	98	82	141	132	124
FUEL CONSUMPTION	85	90	95	230	270	320	165	195	235	135	145	155
MAINTAIN-ABILITY	.5	1	8	.5	1	8	.5	1	8	.5	1	8
ADDITIONAL TRAINING	10	40	80	10	40	80	10	40	80	10	40	80
CARGO CAPACITY	9000	12000	20000	9000	12000	20000	9000	12000	20000	9000	12000	20000
PASSENGER CAPACITY	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 15
UPPER MISSISSIPPI RIVER ICEBREAKER (140' WTGB)

ATTRIBUTE	CHANNEL CLEARING			RESPONSE			BREAKOUT			RIVER OPS		
	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX
ICE DISPLACEMENT	40	70	90	85	95	100	85	95	100	30	50	75
MAX THICKNESS RAMMING	24	30	36	24	30	36	24	30	36	24	30	36
MAX THICKNESS CONTINUOUS	20	24	30	20	24	30	20	24	30	20	24	30
OPEN WATER ACCELERATION	2.0	3.0	5.0	2.0	3.0	5.0	2.0	3.0	5.0	2.0	3.0	5.0
SPEED	4.0	5.0	6.0	3.5	4.0	5.0	3.5	4.0	5.0	4.0	5.0	6.0
TRACK WIDTH	45	45	45	40	45	50	40	45	50	45	45	45
MANEUVER-ABILITY	780	960	1040	660	780	940	660	780	940	720	900	980
AVAILABILITY	40	60	85	40	60	85	40	60	85	40	60	85
ENDURANCE	70	64	60	40	47	43	64	60	57	64	60	57
FUEL CONSUMPTION	275	295	315	375	415	445	295	315	335	295	315	335
MAINTAIN-ABILITY	10	48	72	10	48	72	10		72	10	48	72
ADDITIONAL TRAINING	80	240	480	80	240	480	80	240	480	80	240	480
CARGO CAPACITY	5000	6000	8000	5000	6000	8000	5000	6000	8000	5000	6000	8000
PASSENGER CAPACITY	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 16
140' WTGB WITH BUBBLERS AND HULL COATING; WITHOUT AUXILIARY DEVICE

ATTRIBUTE	CHANNEL CLEARING			RESPONSE			BREAKOUT			RIVER OPS		
	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX
ICE DISPLACEMENT	5	20	50	5	30	60	5	15	30	0	10	20
MAX THICKNESS RAMMING	30	40	70	30	40	70	30	40	70	30	40	70
MAX THICKNESS CONTINUOUS	19	21	24	19	21	24	19	21	24	19	21	24
OPEN WATER ACCELERATION	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0
SPEED	12.0	12.5	13.5	7.9	8.9	9.9	8.0	9.0	10.0	0.5	11.0	12.5
TRACK WIDTH	38	40	45	38	45	60	38	45	60	38	40	44
MANEUVER-ABILITY	390	480	520	330	390	470	330	390	470	360	450	490
AVAILABILITY	90	95	99	90	95	99	90	95	99	90	95	99
ENDURANCE	203	194	184	97	92	88	196	186	178	196	186	178
FUEL CONSUMPTION	95	100	105	200	210	220	99	104	104	99	104	78
MAINTAIN-ABILITY	0	0	0	0	0	0	0	0	0	0	0	0
ADDITIONAL TRAINING	0	0	0	0	0	0	0	0	0	0	0	0
CARGO CAPACITY	2000	3000	5000	2000	3000	5000	2000	3000	5000	2000	3000	5000
PASSENGER CAPACITY	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 17
WATER HULL LUBRICATION (140' WTGB)

ATTRIBUTE	CHANNEL CLEARING			RESPONSE			BREAKOUT			RIVER OPS		
	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX
ICE DISPLACEMENT	5	20	50	5	30	60	5	15	30	0	10	20
MAX THICKNESS RAMMING	30	40	70	30	40	70	30	40	70	30	40	70
MAX THICKNESS CONTINUOUS	19	21	24	19	21	24	19	21	24	19	21	24
OPEN WATER ACCELERATION	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0
SPEED	12.0	12.5	13.4	7.9	8.9	9.9	8.0	9.0	10.0	9.5	11.0	12.5
TRACK WIDTH	38	41	45	38	45	60	38	45	60	38	40	44
MANEUVER-ABILITY	390	480	520	330	390	470	330	390	470	360	450	490
AVAILABILITY	90	95	99	90	95	99	90	95	99	90	95	99
ENDURANCE	137	133	128	78	76	73	133	128	123	133	128	123
FUEL CONSUMPTION	140	145	150	245	255	265	145	150	155	145	150	155
MAINTAIN-ABILITY	0	0	0	0	0	0	0	0	0	0	0	0
ADDITIONAL TRAINING	0	0	0	0	0	0	0	0	0	0	0	0
CARGO CAPACITY	1500	2500	4500	1500	2500	4500	1500	2500	4500	1500	2500	4500
PASSENGER CAPACITY	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 18
EXPLOSIVE ICE BREAKER (140' WTGB)

ATTRIBUTE	CHANNEL CLEARING			RESPONSE			BREAKOUT			RIVER OPS		
	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX
ICE DISPLACEMENT	5	20	40	5	25	50	5	15	30	0	8	17
MAX THICKNESS RAMMING	30	45	80	30	45	80	30	45	80	30	45	80
MAX THICKNESS CONTINUOUS	21	24	30	21	24	30	21	24	30	21	24	30
OPEN WATER ACCELERATION	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0	1.6	2.3	3.0
SPEED	11	13.5	14.5	5.0	8.0	11.0	5.0	8.3	12	10	12.0	13.0
TRACK WIDTH	38	40	45	40	50	65	40	50	65	38	40	44
MANEUVER-ABILITY	390	480	520	330	380	470	330	390	470	360	450	490
AVAILABILITY	70	80	95	70	80	95	70	80	95	70	80	95
ENDURANCE	97	68	51	60	47	39	86	63	49	81	63	49
FUEL CONSUMPTION	198	285	272	320	406	492	225	306	387	225	306	387
MAINTAIN-ABILITY	0	0	0	0	0	0	0	0	0	0	0	0
ADDITIONAL TRAINING	0	0	0	0	0	0	0	0	0	0	0	0
CARGO CAPACITY	2000	3000	5000	2000	3000	5000	2000	3000	5000	2000	3000	5000
PASSENGER CAPACITY	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 19
140' WTGB WITH BILGE KEELS

ATTRIBUTE	CHANNEL CLEARING			RESPONSE			BREAKOUT			RIVER OPS		
	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX	MIN	M.P.	MAX
ICE DISPLACEMENT	50	65	90	60	85	95	60	85	95	10	40	70
MAX THICKNESS RAMMING	24	30	32	24	30	36	24	30	36	24	30	36
MAX THICKNESS CONTINUOUS	13	17	20	13	17	20	13	17	20	13	17	20
OPEN WATER ACCELERATION	1.7	3.0	4.0	1.7	3.0	4.0	1.7	3.0	4.0	1.7	3.0	4.0
SPEED	7	11	13	4.0	6.2	8.0	4.2	6.4	8.2	5.0	9.0	11.5
TRACK WIDTH	38	40	45	38	45	60	38	45	60	38	40	44
MANEUVER-ABILITY	390	480	520	330	390	470	330	390	470	360	450	490
AVAILABILITY	100	100	100	100	100	100	100	100	100	100	100	100
ENDURANCE	277	255	240	114	108	102	180	174	166	194	185	176
FUEL CONSUMPTION	70	75	80	170	180	190	105	110	115	98	103	108
MAINTAIN-ABILITY	0	0	0	0	0	0	0	0	0	0	0	0
ADDITIONAL TRAINING	0	0	0	0	0	0	0	0	0	0	0	0
CARGO CAPACITY	5000	6000	8000	5000	6000	8000	5000	6000	8000	5000	6000	8000
PASSENGER CAPACITY	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX E

ZERO PREFERENCES FOR EACH DEVICE

	Breakout	Channel Clearing	Response	River Ops	Platform Capability
Ice Displacement	1	1		3	
Maximum Thickness, Ramming	6	4	6	7	10
Maximum Thickness, Continuous	7	6	6	5	
Open Water Acceleration	2	1	1	4	
Ship Speed	3		1	1	10
Track Width	5	8		3	14
Maneuvera-bility	6	7	5	9	1
Availability				1	
Endurance	2		7	3	10
Fuel Consumption	1	1	2	2	1
Maintaina-bility				1	9
Additional Training Required					
Cargo Capacity					1
Passenger Capacity					13

	Breakout	Channel Clearing	Response	River Ops	Platform Capability
Ice Displacement	5	2		7	
Maximum Thickness, Ramming	4	2	2	3	
Maximum Thickness, Continuous				2	
Open Water Acceleration	1			3	
Ship Speed	1			1	9
Track Width		8	1	4	9
Maneuverability	3	7	3	8	1
Availability	1		1	2	
Endurance			7	1	9
Fuel Consumption	1	1	5	2	1
Maintainability					
Additional Training Required					
Cargo Capacity					1
Passenger Capacity					13

	Breakout	Channel Clearing	Response	River Ops	Platform Capability
Ice Displacement	1	1		2	
Maximum Thickness, Ramming	4	2	2	3	
Maximum Thickness, Continuous	3	1	2	2	
Open Water Acceleration	1			3	
Ship Speed	2			1	9
Track Width	4	7		4	9
Maneuvera-bility	3	7	1	8	1
Availability	2	2	2	2	
Endurance	2	2	8	3	10
Fuel Consumption	1	1	5	2	1
Maintaina-bility					
Additional Training Required				1	
Cargo Capacity					1
Passenger Capacity					13

	Breakout	Channel Clearing	Response	River Ops	Platform Capability
Ice Displacement	6	3		9	1
Maximum Thickness, Ramming	4	2	2	3	
Maximum Thickness, Continuous	6	4	5	3	
Open Water Acceleration	1			3	
Ship Speed	2			1	10
Track Width	6	8		5	9
Maneuvera-bility	6	7	5	9	1
Availability					
Endurance			7	1	9
Fuel Consumption	1	1	2	2	1
Maintaina-bility					
Additional Training Required					
Cargo Capacity					1
Passenger Capacity					13

	Breakout	Cnannel Clearing	Response	River Ops	Platform Capability
Ice Displacement	2	3		9	1
Maximum Thickness, Ramming	4	2	2	3	
Maximum Thickness, Continuous	2		1	2	
Open Water Acceleration	1			3	
Ship Speed	5			1	10
Track Width		7		5	9
Maneuvera-bility	10	6	10	9	1
Availability	1		1		
Endurance	7		8	1	9
Fuel Consumption	2	1	5	2	1
Maintaina-bility					
Additional Training Required	13		13		
Cargo Capacity					1
Passenger Capacity					13

	Breakout	Channel Clearing	Response	River Ops	Platform Capability
Ice Displacement	2	3		9	1
Maximum Thickness, Ramming	4	2	2	3	
Maximum Thickness, Continuous	2		2	2	
Open Water Acceleration	1			3	
Ship Speed	5			1	10
Track Width		8		5	9
Maneuvera-bility	3	7	2	9	1
Availability	1		1		
Endurance	8		10	1	9
Fuel Consumption	5	1	5	2	1
Maintaina-bility					
Additional Training Required	12		12		
Cargo Capacity					1
Passenger Capacity					13

	Breakout	Channel Clearing	Response	River Ops	Platform Capability
Ice Displacement	6	3		9	1
Maximum Thickness, Ramming	4	2	2	3	
Maximum Thickness, Continuous	6	4	5	3	
Open Water Acceleration	1			3	
Ship Speed	2			1	10
Track Width	6	8		5	9
Maneuvera-bility	3	7	2	9	1
Availability					
Endurance			7	1	9
Fuel Consumption	1	1	2	2	1
Maintaina-bility					
Additional Training Required					
Cargo Capacity					1
Passenger Capacity					13

	Breakout	Channel Clearing	Response	River Ops	Platform Capability
Ice Displacement	1	1		3	
Maximum Thickness, Ramming	6	4	5	7	9
Maximum Thickness, Continuous	3	1	2	2	
Open Water Acceleration	2	1	1	4	
Ship Speed	1			1	10
Track Width	7	8		5	9
Maneuverability	3	7	2	9	1
Availability				1	
Endurance			7	1	9
Fuel Consumption	1	1	2	2	1
Maintainability					9
Additional Training Required					
Cargo Capacity					1
Passenger Capacity					13

	Breakout	Channel Clearing	Response	River Ops	Platform Capability
Ice Displacement	5	2		9	1
Maximum Thickness, Ramming	4	2	2	3	
Maximum Thickness, Continuous	5	3	5	3	
Open Water Acceleration	1			3	
Ship Speed	1			1	10
Track Width	6	8		5	9
Maneuvera-bility	3	7	2	9	1
Availability				1	
Endurance			8	1	9
Fuel Consumption	1	1	5	2	1
Maintaina-bility					
Additional Training Required					
Cargo Capacity					1
Passenger Capacity					13

	Breakout	Channel Clearing	Response	River Ops	Platform Capability
Ice Displacement	1	1		2	
Maximum Thickness, Ramming	6	5	7	8	9
Maximum Thickness, Continuous	7	8	7	6	1
Open Water Acceleration	2	1	1	4	
Ship Speed	3			1	10
Track Width	6	8		5	9
Maneuvera-bility	3	7	2	9	1
Availability					
Endurance			7	1	9
Fuel Consumption	1	1	2	2	1
Maintaina-bility					
Additional Training Required					
Cargo Capacity					1
Passenger Capacity					13

	Breakout	Channel Clearing	Response	River Ops	Platform Capability
Ice Displacement	1	1		3	
Maximum Thickness, Ramming	6	4	7	8	10
Maximum Thickness, Continuous	2		1	2	
Open Water Acceleration	1			3	
Ship Speed	5		2	3	10
Track Width		7		3	9
Maneuvera-bility	12	10	12	13	3
Availability	1	1	1	2	
Endurance	2		8	3	10
Fuel Consumption	2	1	5	2	1
Maintaina-bility				1	9
Additional Training Required	13	13	13	13	3
Cargo Capacity					
Passenger Capacity					13

	Breakout	Channel Clearing	Response	River Ops	Platform Capability
Ice Displacement	5	2		9	1
Maximum Thickness, Ramming	4	2	2	3	
Maximum Thickness, Continuous	2		1	2	
Open Water Acceleration	5	4	4	5	1
Ship Speed	2			1	9
Track Width					
Maneuvera-bility	3	7	2	9	1
Availability	10	10	11	11	3
Endurance	4	2	8	3	10
Fuel Consumption	1	1	5	2	1
Maintaina-bility	6	6	6	7	10
Additional Training Required	7	7	7	8	2
Cargo Capacity					
Passenger Capacity					13

140 - NO AUXILIARY DEVICES

	Breakout	Channel Clearing	Response	River Ops	Platform Capability
Ice Displacement	6	3		9	1
Maximum Thickness, Ramming	5	3	3	4	9
Maximum Thickness, Continuous	7	5	6	4	
Open Water Acceleration	1			3	
Ship Speed	3			1	10
Track Width	6	8		5	9
Maneuvera-bility	3	7	2	9	1
Availability					
Endurance			7	1	9
Fuel Consumption	1	1	2	2	1
Maintaina-bility					
Additional Training Required					
Cargo Capacity					1
Passenger Capacity					13

	Breakout	Channel Clearing	Response	River Ops	Platform Capability
Ice Displacement	6	2		9	1
Maximum Thickness, Ramming	4	2	2	3	
Maximum Thickness, Continuous	5	3	5	3	
Open Water Acceleration	1			3	
Ship Speed	1			1	10
Track Width	6	8		5	9
Maneuvera-bility	3	7	2	9	1
Availability				1	
Endurance	3	3	8	3	10
Fuel Consumption	1	1	5	2	1
Maintaina-bility					
Additional Training Required					
Cargo Capacity					1
Passenger Capacity					13

	Breakout	Channel Clearing	Response	River Ops	Platform Capability
Ice Displacement	6	3		9	1
Maximum Thickness, Ramming	4	2	2	3	
Maximum Thickness, Continuous	4	2	3	3	
Open Water Acceleration	4	3	3	5	3
Ship Speed	2			1	9
Track Width	6	8		5	9
Maneuvera-bility	4	7	2	9	1
Availability	2	2	2	3	
Endurance			8	1	9
Fuel Consumption	1	1	5	2	1
Maintaina-bility				1	9
Additional Training Required	1	1	1	2	
Cargo Capacity					
Passenger Capacity					13

	Breakout	Channel Clearing	Response	River Ops	Platform Capability
Ice Displacement	6	3		9	1
Maximum Thickness, Ramming	4	2	2	3	
Maximum Thickness, Continuous	3		2	2	
Open Water Acceleration	1			3	
Ship Speed	2			1	1
Track Width	5	8		5	
Maneuverability	2	7	2	9	1
Availability	2		2		
Endurance	2		7	1	
Fuel Consumption	1	1	5	2	1
Maintainability					
Additional Training Required	10	10	10	11	13
Cargo Capacity					1
Passenger Capacity					13

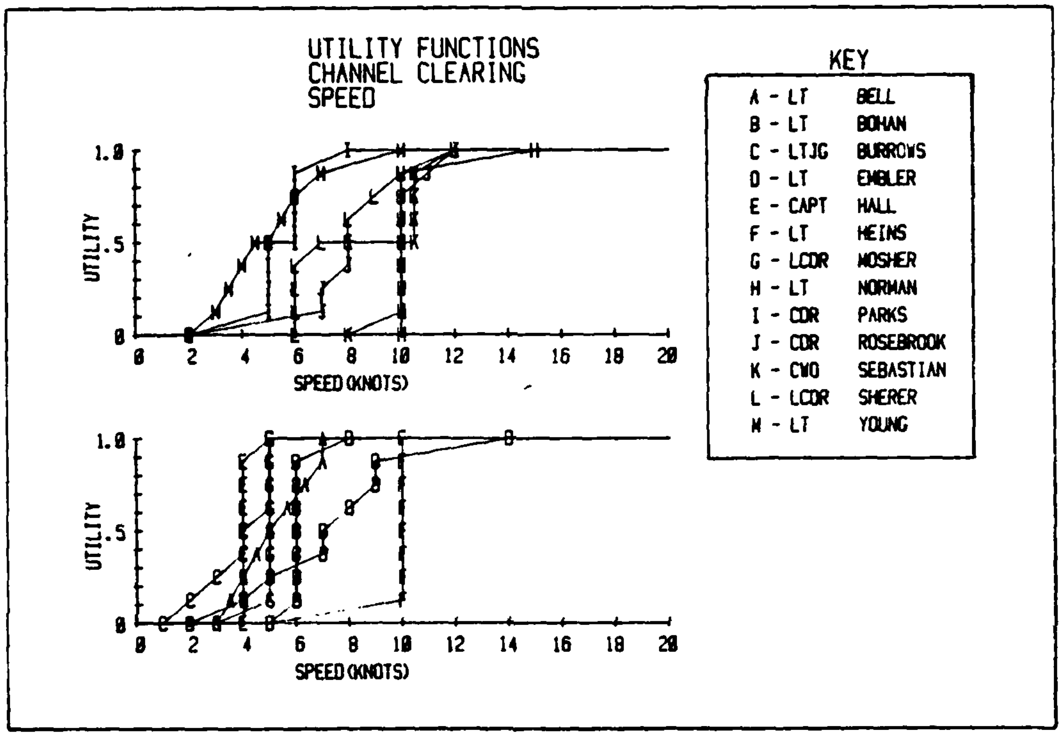
	Breakout	Channel Clearing	Response	River Ops	Platform Capability
Ice Displacement	6	3		9	1
Maximum Thickness, Ramming	4	2	2	3	
Maximum Thickness, Continuous	4	2	3	3	
Open Water Acceleration	1			3	
Ship Speed	2			1	9
Track Width	3	5		2	9
Maneuvera-bility	3	7	2	9	1
Availability	1	1	1	2	
Endurance	7	7	10	7	11
Fuel Consumption	2	1	5	3	1
Maintaina-bility					
Additional Training Required	13	13	13	13	3
Cargo Capacity					1
Passenger Capacity					13

	Breakout	Channel Clearing	Response	River Ops	Platform Capability
Ice Displacement	6	3		9	1
Maximum Thickness, Ramming	4	2	2	3	
Maximum Thickness, Continuous	3		2	2	
Open Water Acceleration	1			3	
Ship Speed	1		1	1	9
Track Width	5	8		5	9
Maneuverability	3	7	2	9	1
Availability	2	2	2	2	
Endurance	8	8	10	8	11
Fuel Consumption	5	5	5	6	2
Maintainability					
Additional Training Required					
Cargo Capacity					1
Passenger Capacity					13

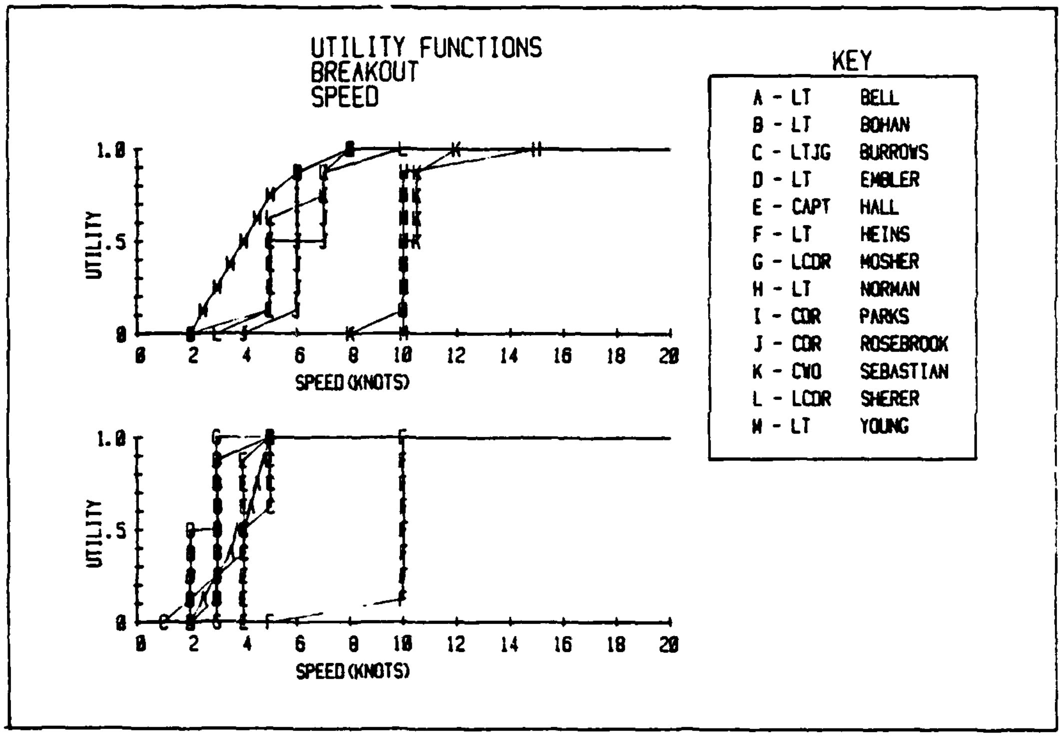
	Breakout	Channel Clearing	Response	River Ops	Platform Capability
Ice Displacement	1	1		2	
Maximum Thickness, Ramming	6	5	7	8	10
Maximum Thickness, Continuous	2		2	2	
Open Water Acceleration	6	5	5	6	1
Ship Speed	4	3	4	4	10
Track Width	7				
Maneuvera-bility	10	11	10	12	3
Availability	3	3	4	4	
Endurance	10	10	11	10	12
Fuel Consumption	5	5	5	6	2
Maintaina-bility	2	2	2	3	10
Additional Training Required	13	13	13	13	3
Cargo Capacity					1
Passenger Capacity					13

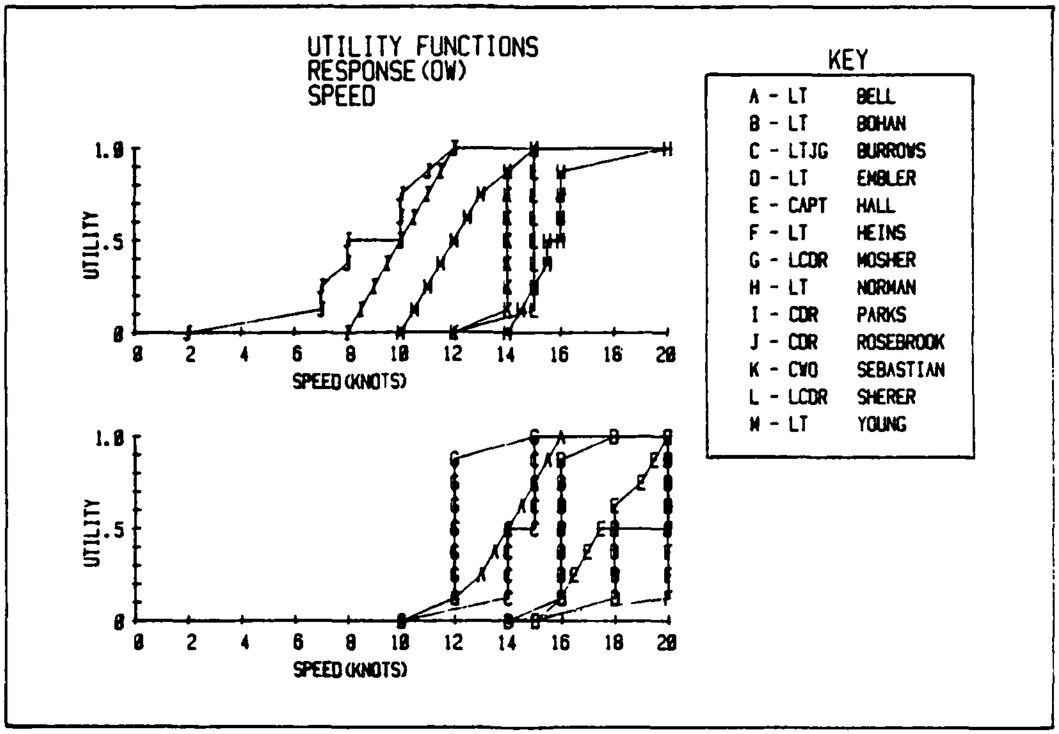
APPENDIX F

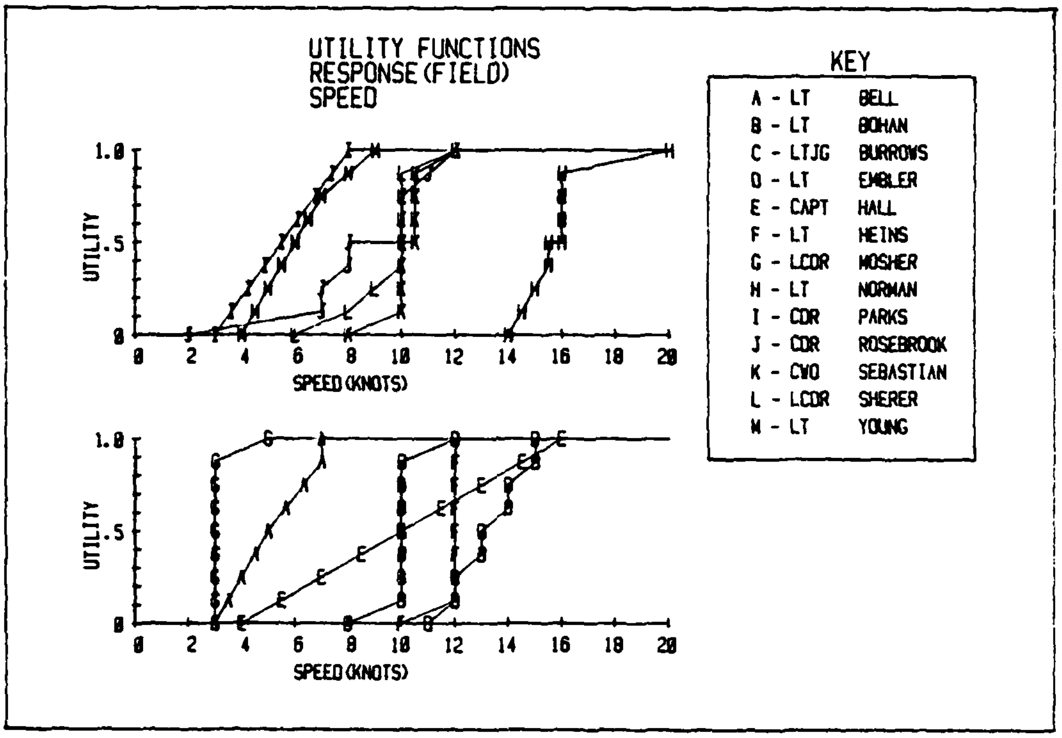
UTILITY FUNCTION PLOTS

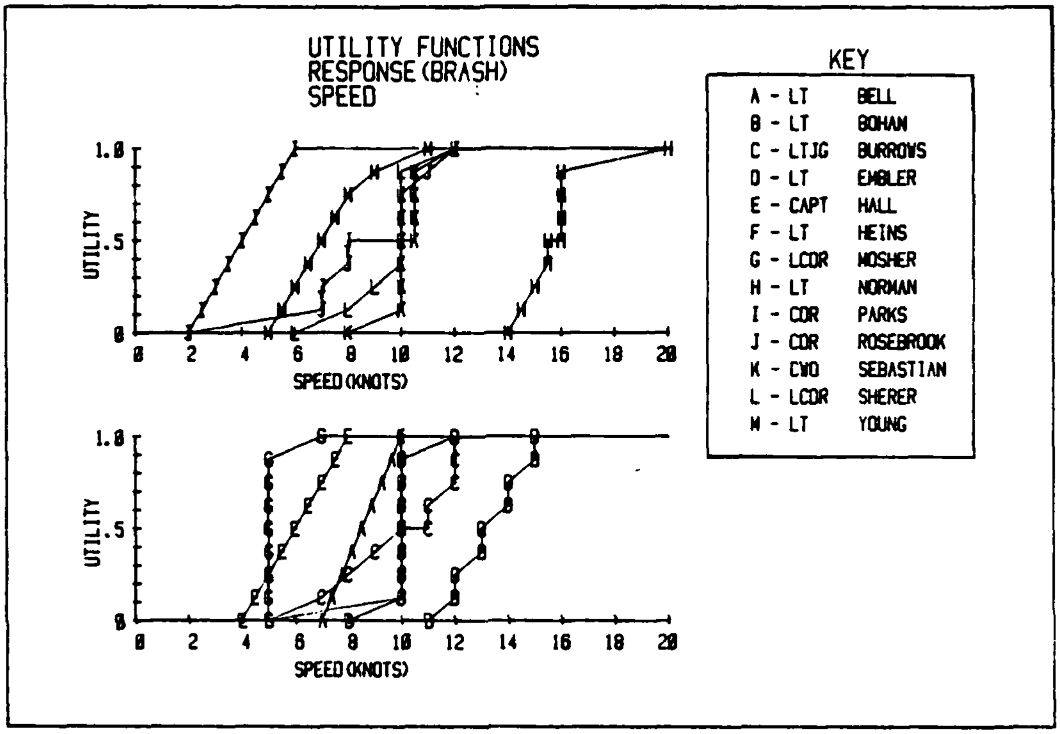


UTILITY FUNCTIONS
CHANNEL CLEARING
SPEED
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
SPEED (KNOTS)

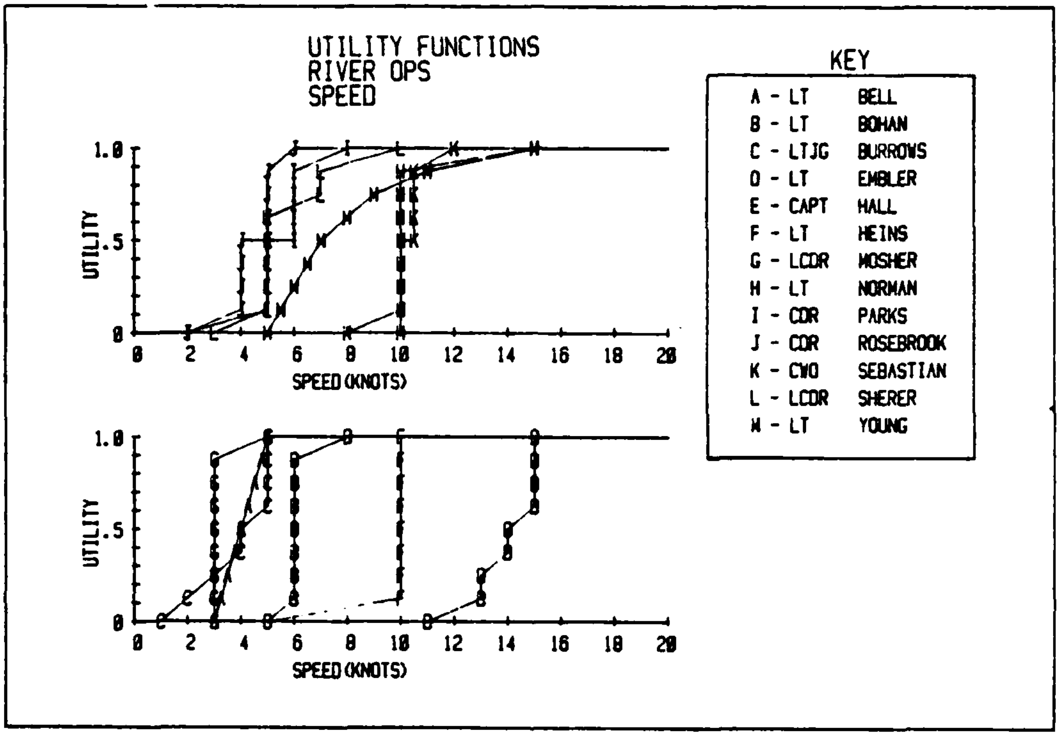

UTILITY FUNCTIONS
BREAKOUT
SPEED
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
SPEED (KNOTS)
UTILITY
SPEED (KNOTS)

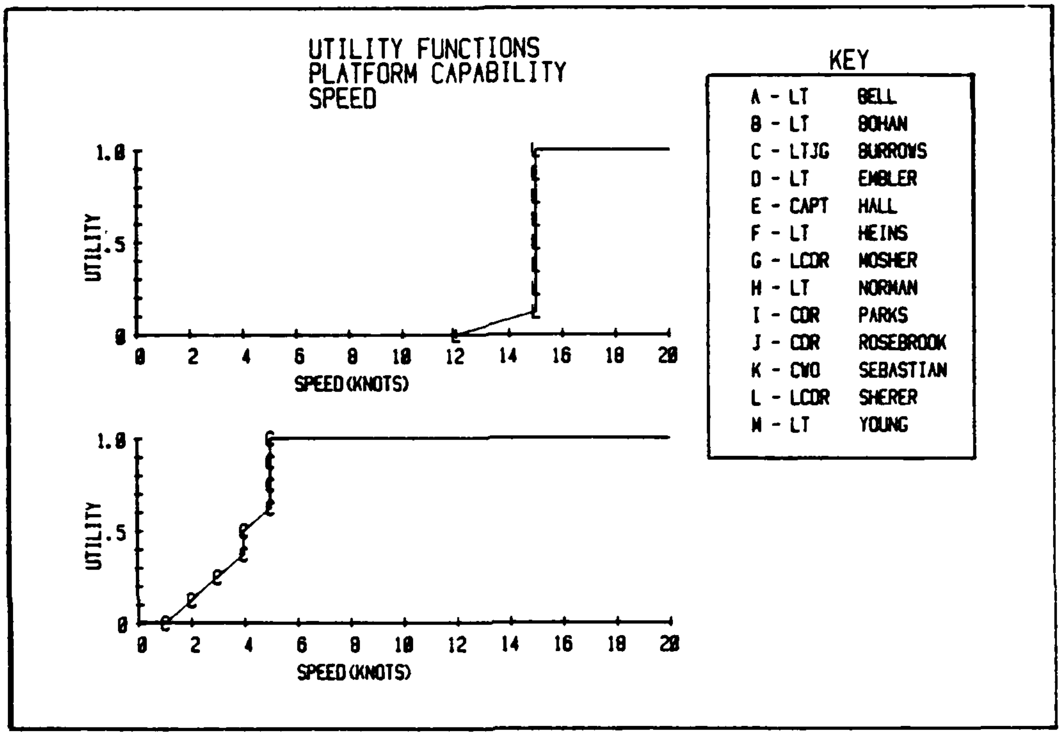

UTILITY FUNCTIONS
RESPONSE (OW)
SPEED
UTILITY
SPEED (KNOTS)
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG

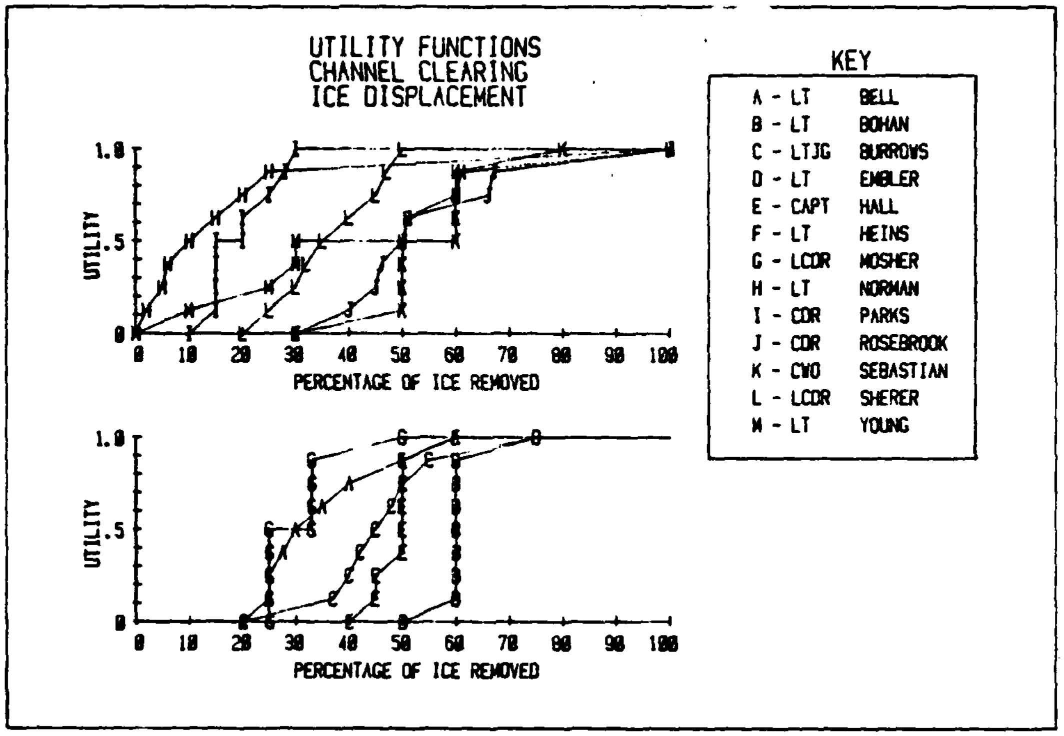

UTILITY FUNCTIONS
RESPONSE (FIELD)
SPEED
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
SPEED (KNOTS)
UTILITY
SPEED (KNOTS)



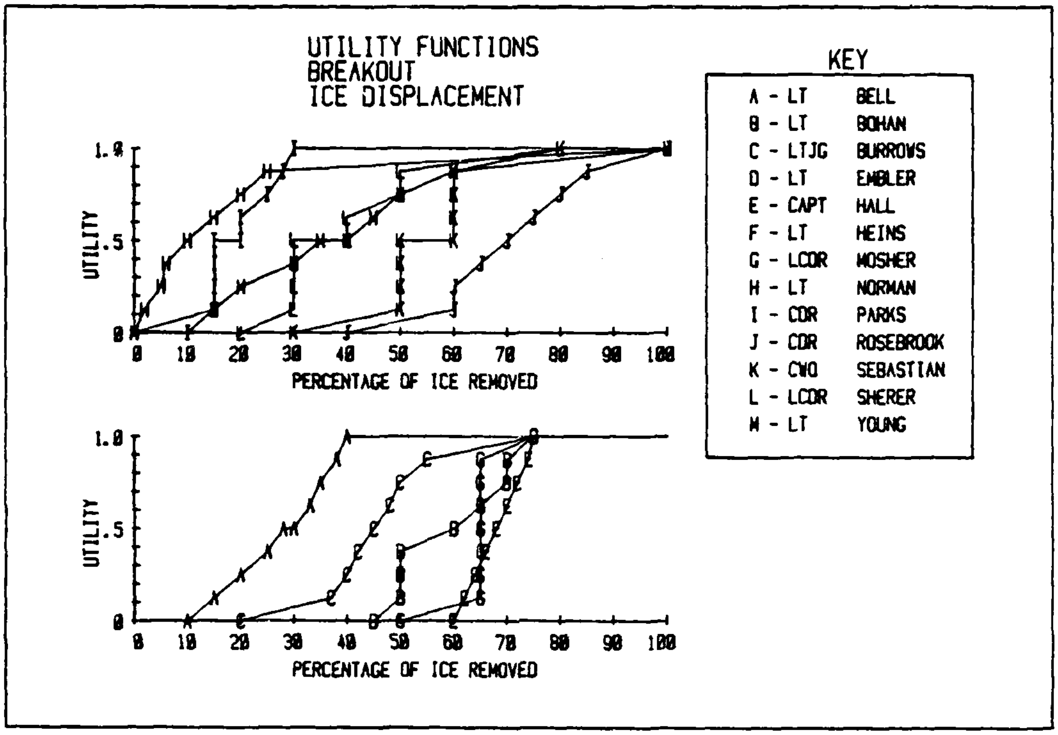
UTILITY FUNCTIONS
RESPONSE (BRASH)
SPEED
UTILITY
1.0
.5
0
0 2 4 6 8 10 12 14 16 18 20
SPEED (KNOTS)
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG

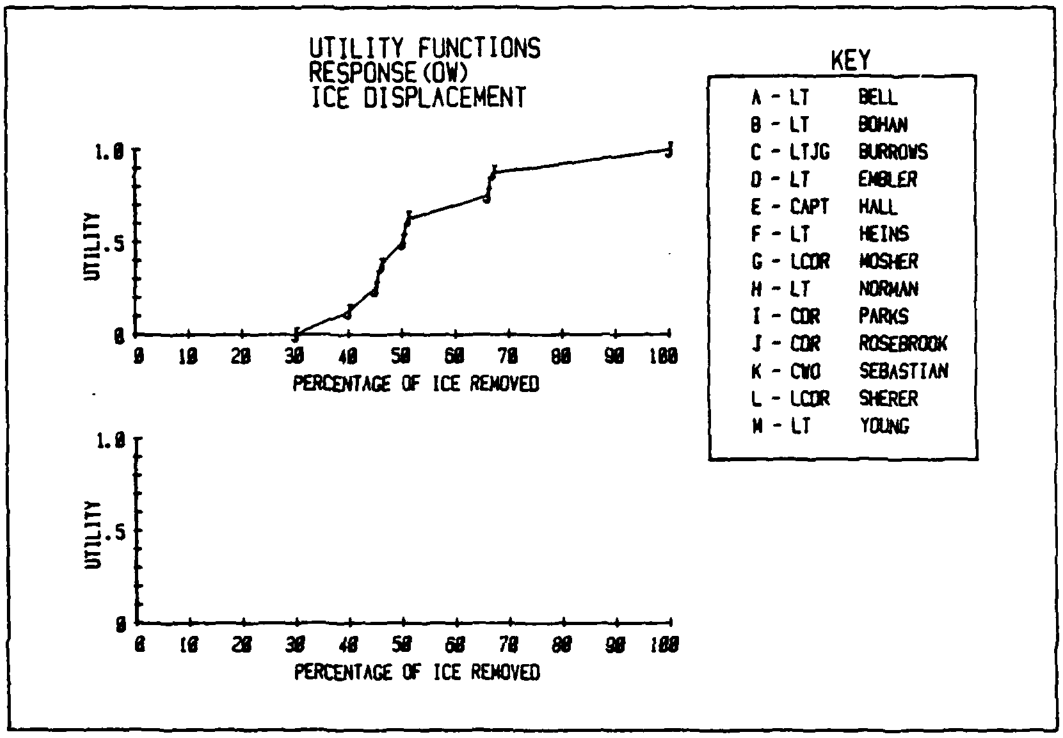

UTILITY FUNCTIONS
RIVER OPS
SPEED
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
SPEED (KNOTS)
UTILITY
SPEED (KNOTS)


UTILITY FUNCTIONS
PLATFORM CAPABILITY
SPEED
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 2 4 6 8 10 12 14 16 18 20
SPEED (KNOTS)
UTILITY
1.0
.5
0
0 2 4 6 8 10 12 14 16 18 20
SPEED (KNOTS)

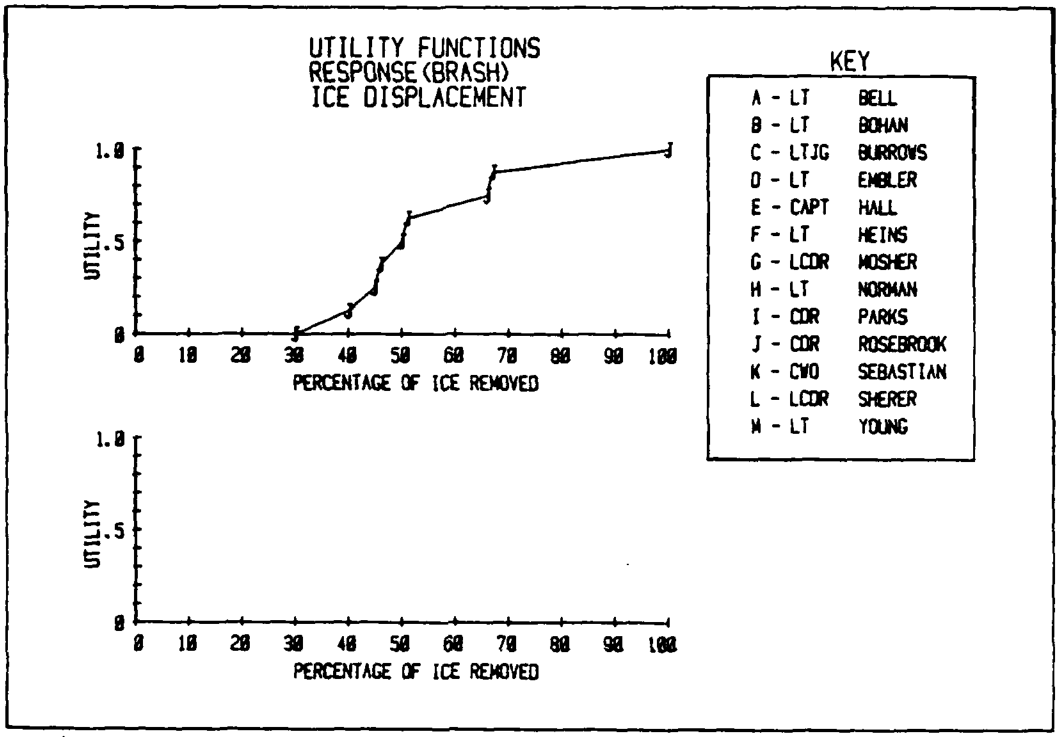


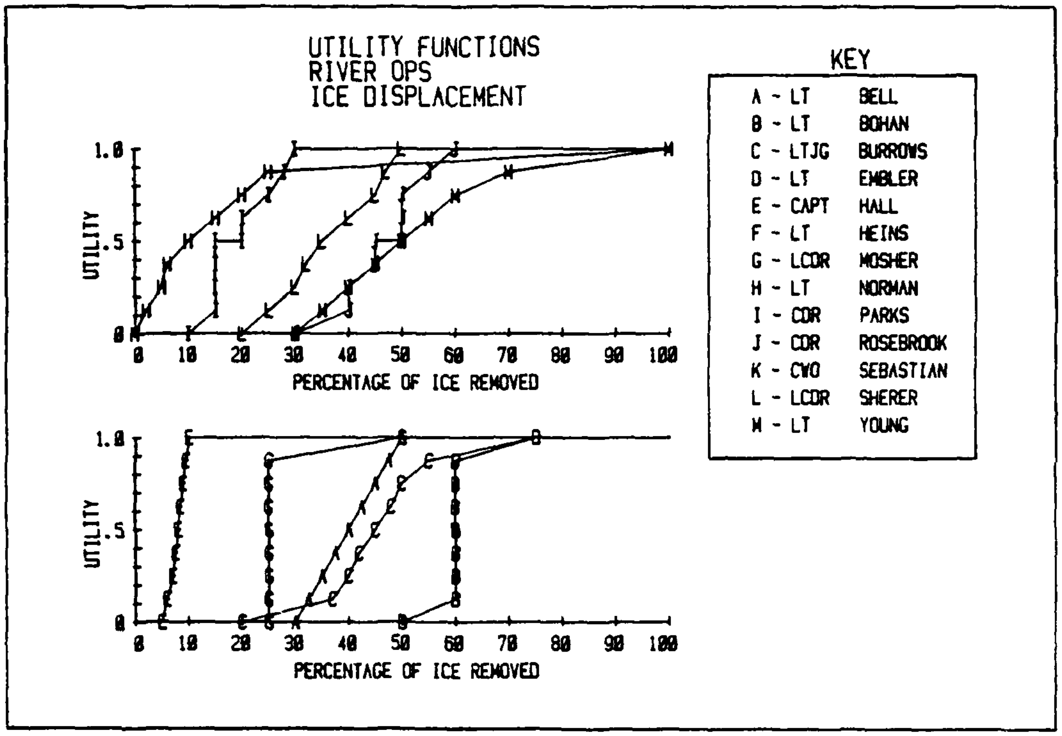
UTILITY FUNCTIONS
CHANNEL CLEARING
ICE DISPLACEMENT
UTILITY
PERCENTAGE OF ICE REMOVED
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG

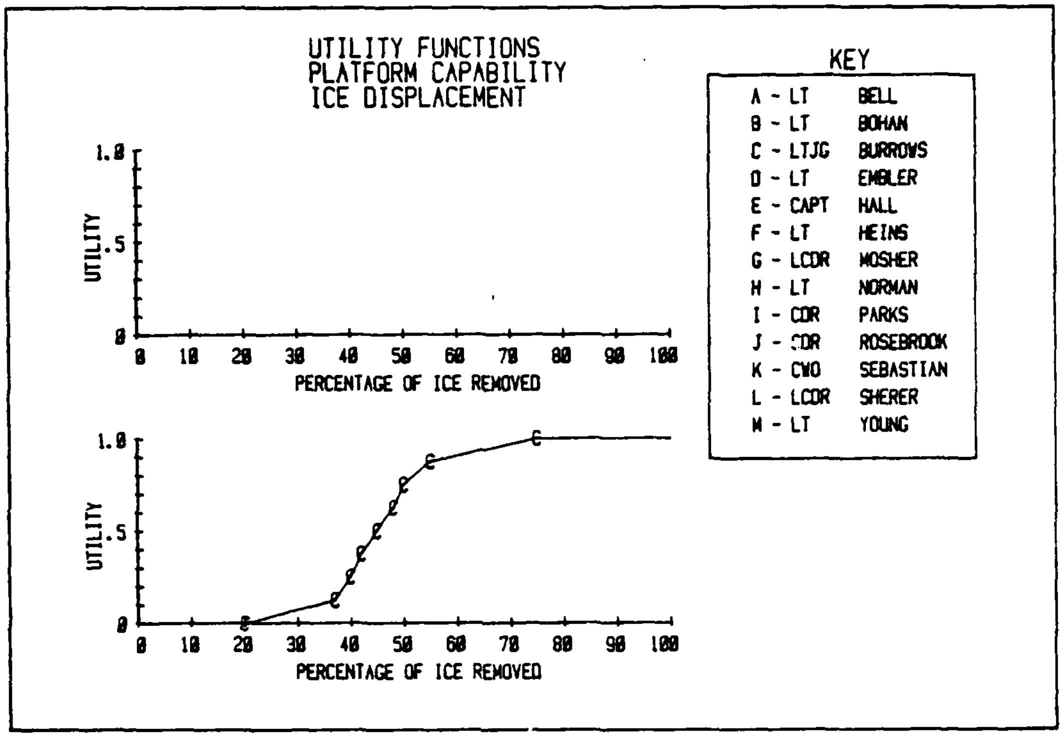

UTILITY FUNCTIONS
BREAKOUT
ICE DISPLACEMENT
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
PERCENTAGE OF ICE REMOVED
UTILITY
PERCENTAGE OF ICE REMOVED

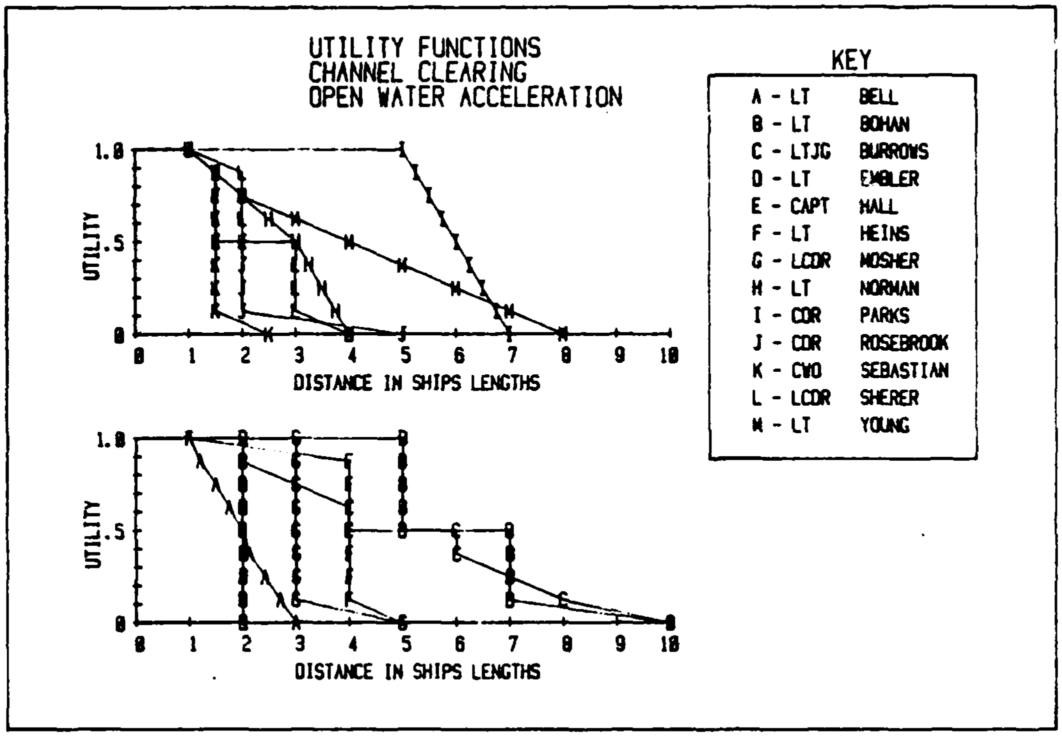


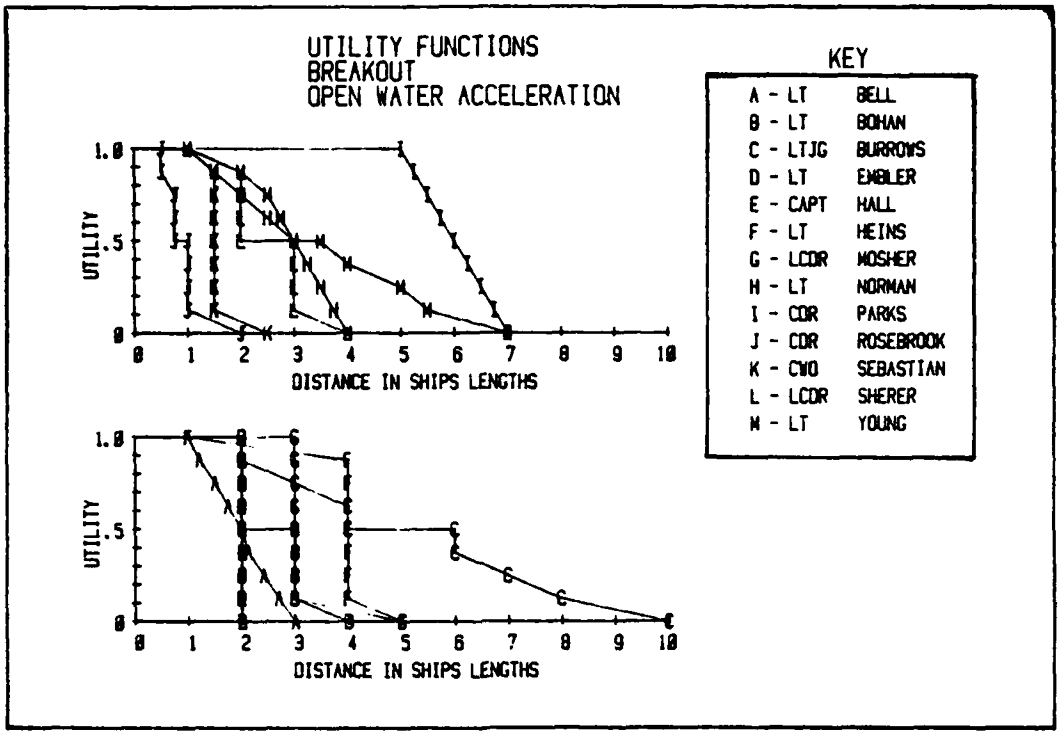
UTILITY FUNCTIONS
RESPONSE (OW)
ICE DISPLACEMENT
UTILITY
PERCENTAGE OF ICE REMOVED
UTILITY
PERCENTAGE OF ICE REMOVED
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG


UTILITY FUNCTIONS
RESPONSE (BRASH)
ICE DISPLACEMENT
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 10 20 30 40 50 60 70 80 90 100
PERCENTAGE OF ICE REMOVED
UTILITY
1.0
.5
0
0 10 20 30 40 50 60 70 80 90 100
PERCENTAGE OF ICE REMOVED


UTILITY FUNCTIONS
RIVER OPS
ICE DISPLACEMENT
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
PERCENTAGE OF ICE REMOVED
UTILITY
PERCENTAGE OF ICE REMOVED


UTILITY FUNCTIONS
PLATFORM CAPABILITY
ICE DISPLACEMENT
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 10 20 30 40 50 60 70 80 90 100
PERCENTAGE OF ICE REMOVED
UTILITY
1.0
.5
0
0 10 20 30 40 50 60 70 80 90 100
PERCENTAGE OF ICE REMOVED


UTILITY FUNCTIONS
CHANNEL CLEARING
OPEN WATER ACCELERATION
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 1 2 3 4 5 6 7 8 9 10
DISTANCE IN SHIPS LENGTHS
UTILITY
1.0
.5
0
0 1 2 3 4 5 6 7 8 9 10
DISTANCE IN SHIPS LENGTHS


UTILITY FUNCTIONS
BREAKOUT
OPEN WATER ACCELERATION
KEY
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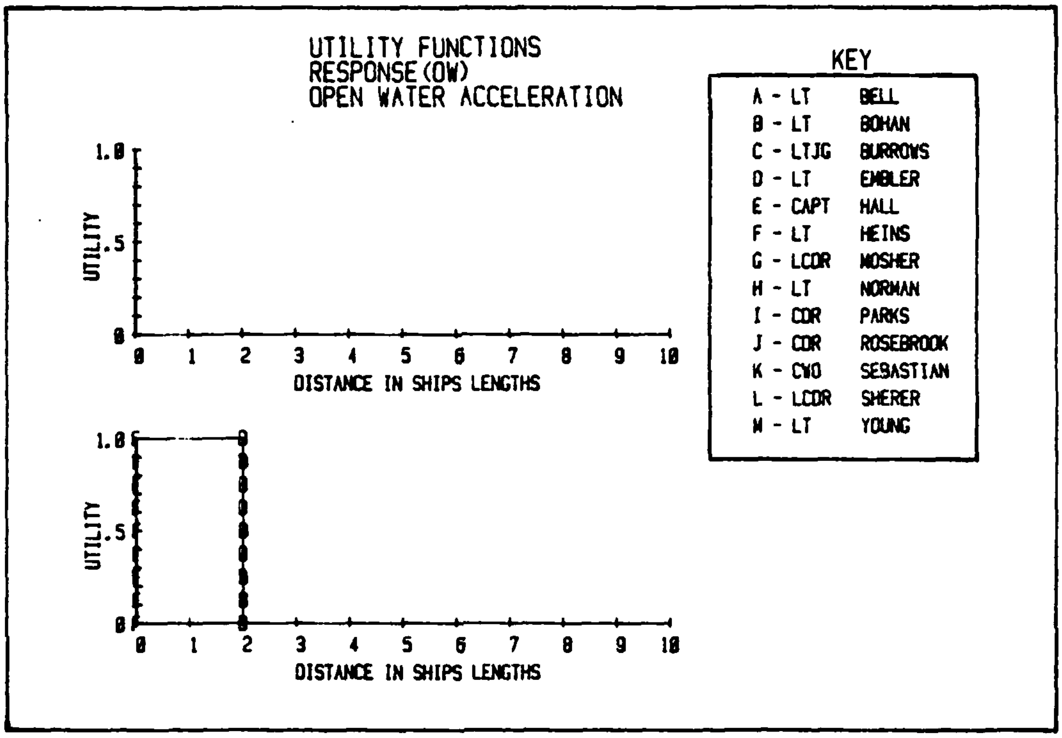
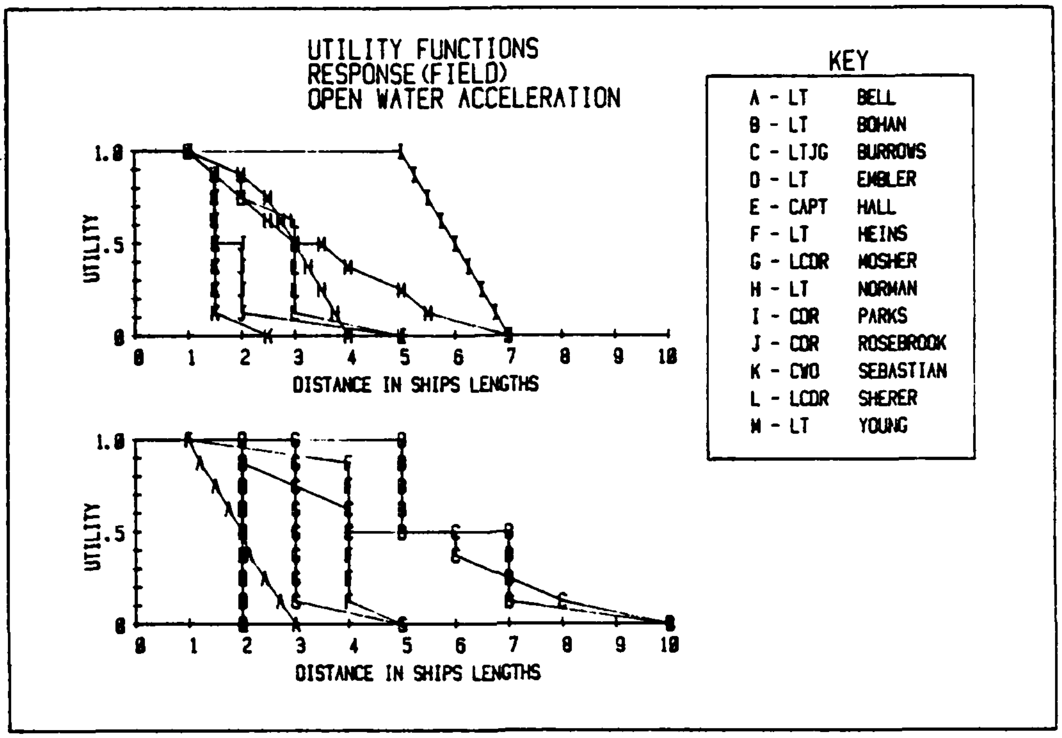
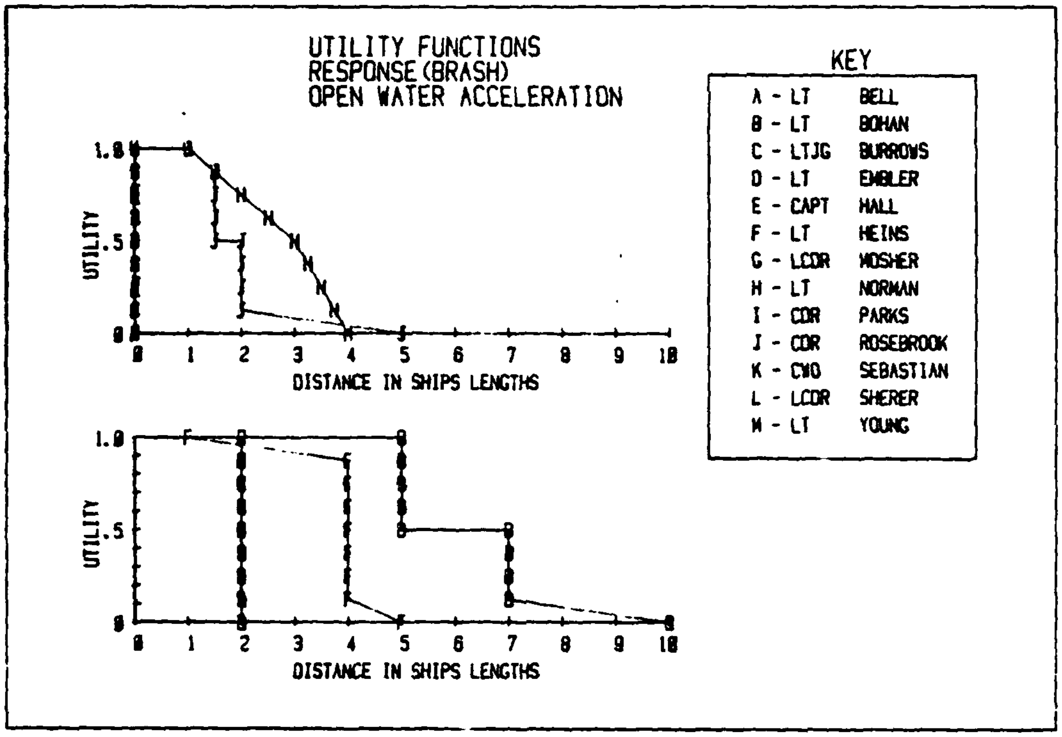
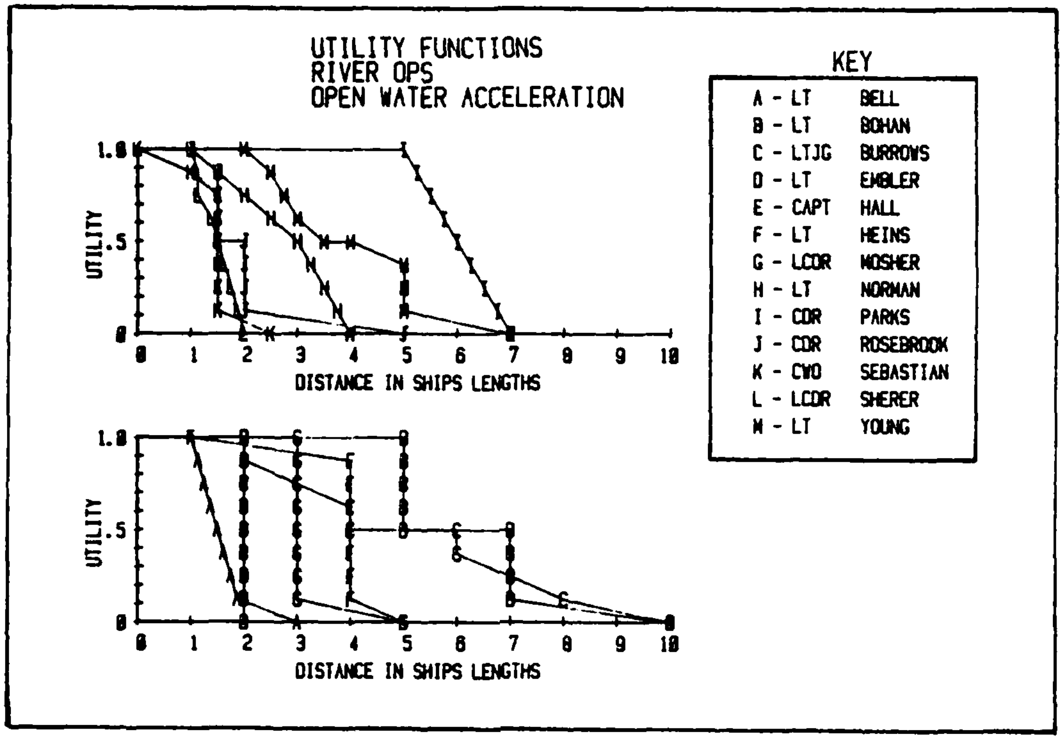
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
DISTANCE IN SHIPS LENGTHS
UTILITY
DISTANCE IN SHIPS LENGTHS

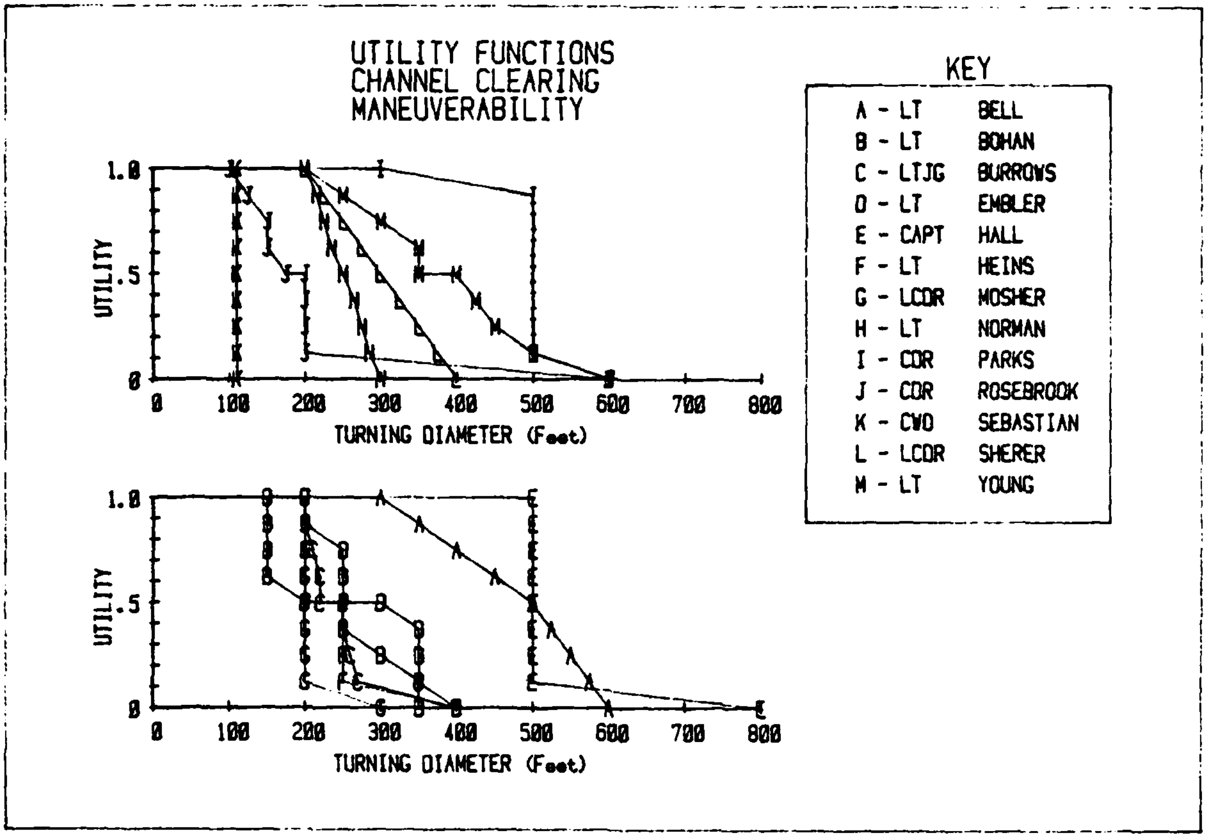

UTILITY FUNCTIONS
RESPONSE (OW)
OPEN WATER ACCELERATION
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 1 2 3 4 5 6 7 8 9 10
DISTANCE IN SHIPS LENGTHS
UTILITY
1.0
.5
0
0 1 2 3 4 5 6 7 8 9 10
DISTANCE IN SHIPS LENGTHS

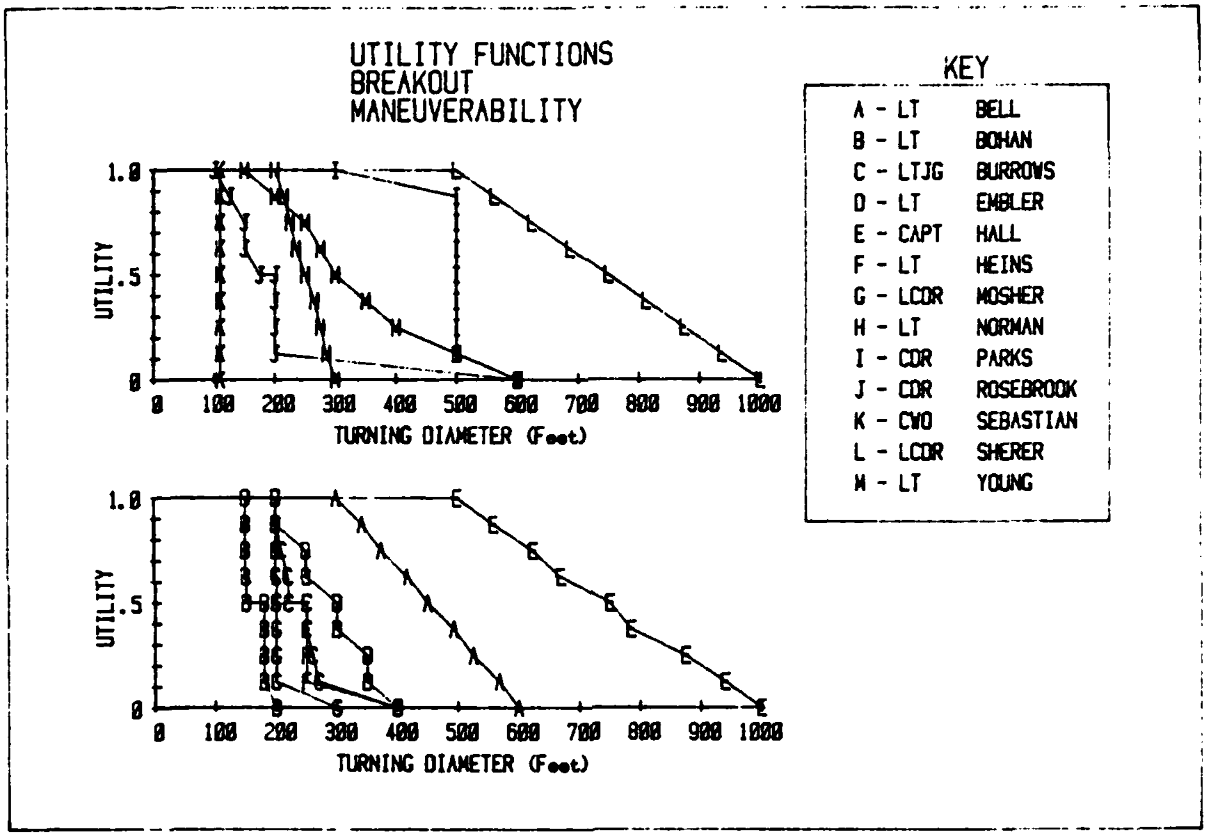

UTILITY FUNCTIONS
RESPONSE (FIELD)
OPEN WATER ACCELERATION
UTILITY
1.0
.5
0
0 1 2 3 4 5 6 7 8 9 10
DISTANCE IN SHIPS LENGTHS
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG

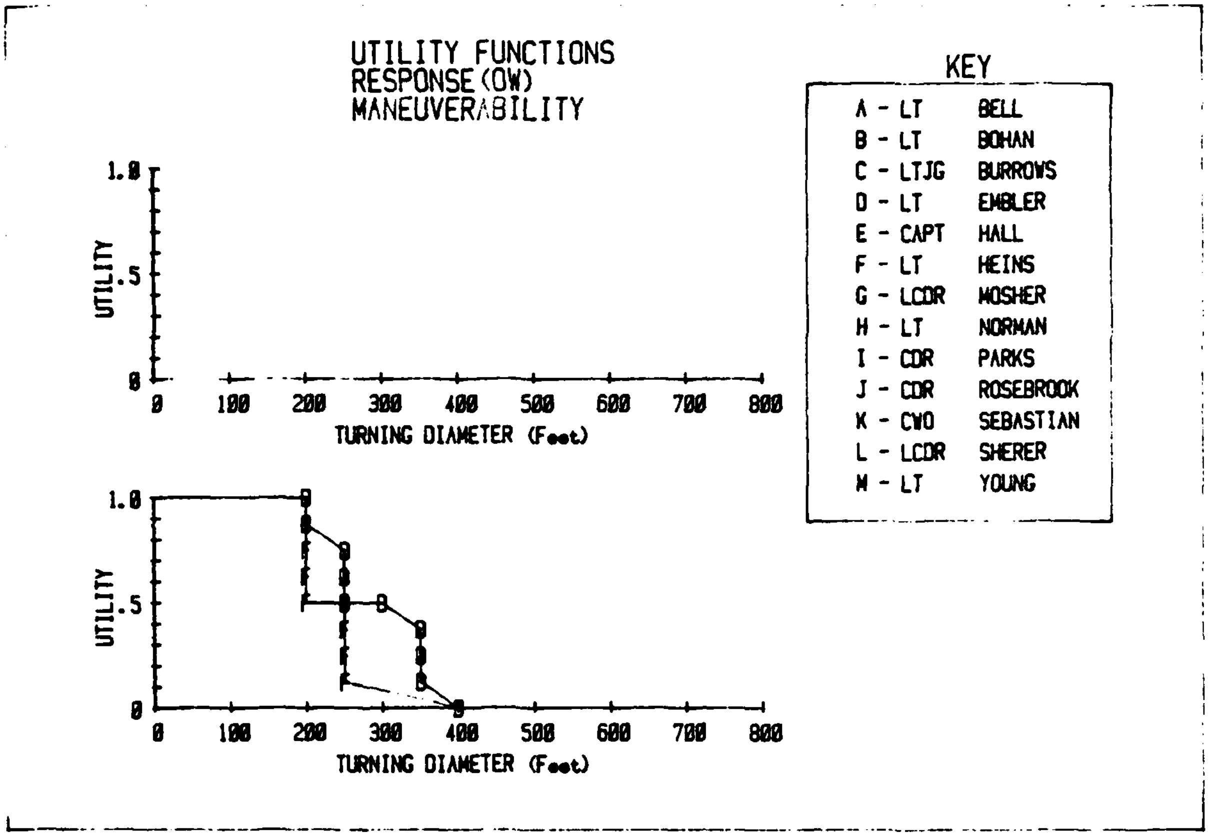

UTILITY FUNCTIONS
RESPONSE (BRASH)
OPEN WATER ACCELERATION
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 1 2 3 4 5 6 7 8 9 10
DISTANCE IN SHIPS LENGTHS
UTILITY
1.0
.5
0
0 1 2 3 4 5 6 7 8 9 10
DISTANCE IN SHIPS LENGTHS

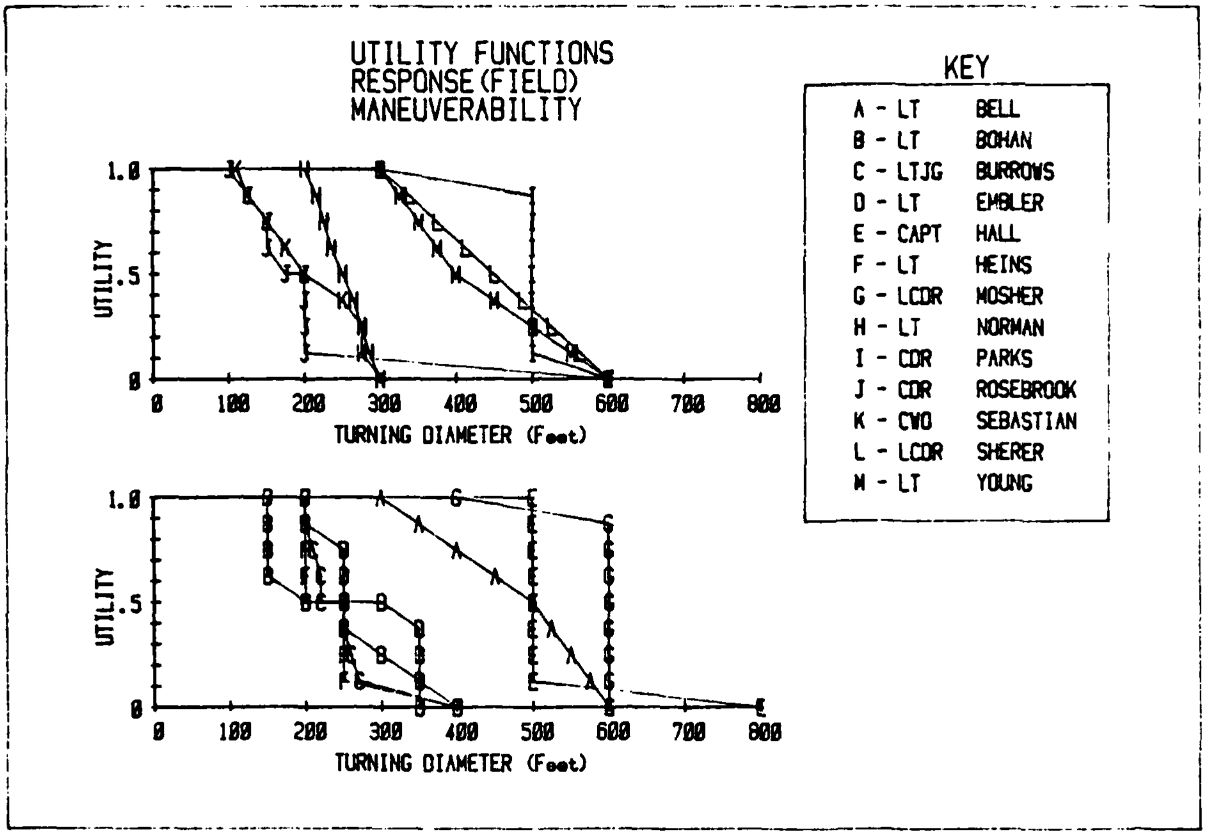


UTILITY FUNCTIONS
RIVER OPS
OPEN WATER ACCELERATION
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
DISTANCE IN SHIPS LENGTHS
UTILITY
DISTANCE IN SHIPS LENGTHS

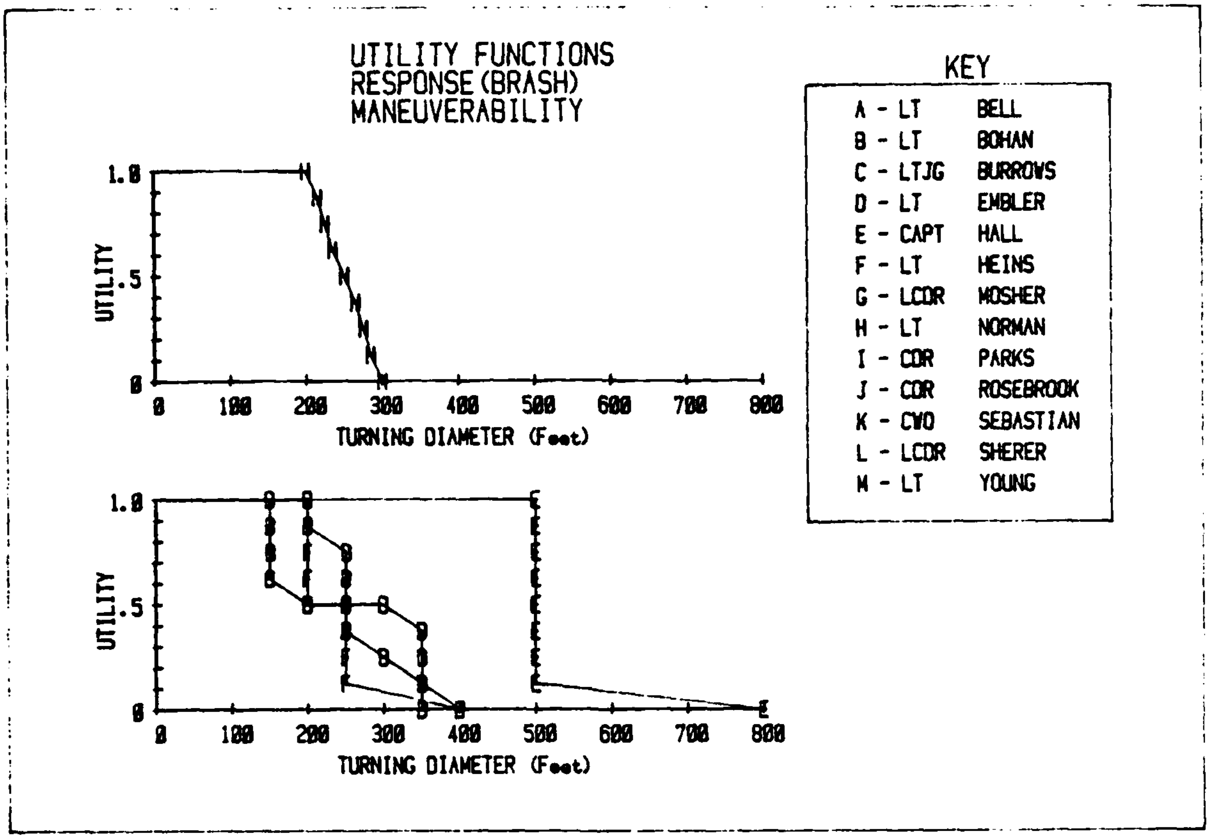

UTILITY FUNCTIONS
CHANNEL CLEARING
MANEUVERABILITY
UTILITY
1.0
.5
0
0 100 200 300 400 500 600 700 800
TURNING DIAMETER (Feet)
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG


UTILITY FUNCTIONS
BREAKOUT
MANEUVERABILITY
UTILITY
TURNING DIAMETER (Feet)
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG

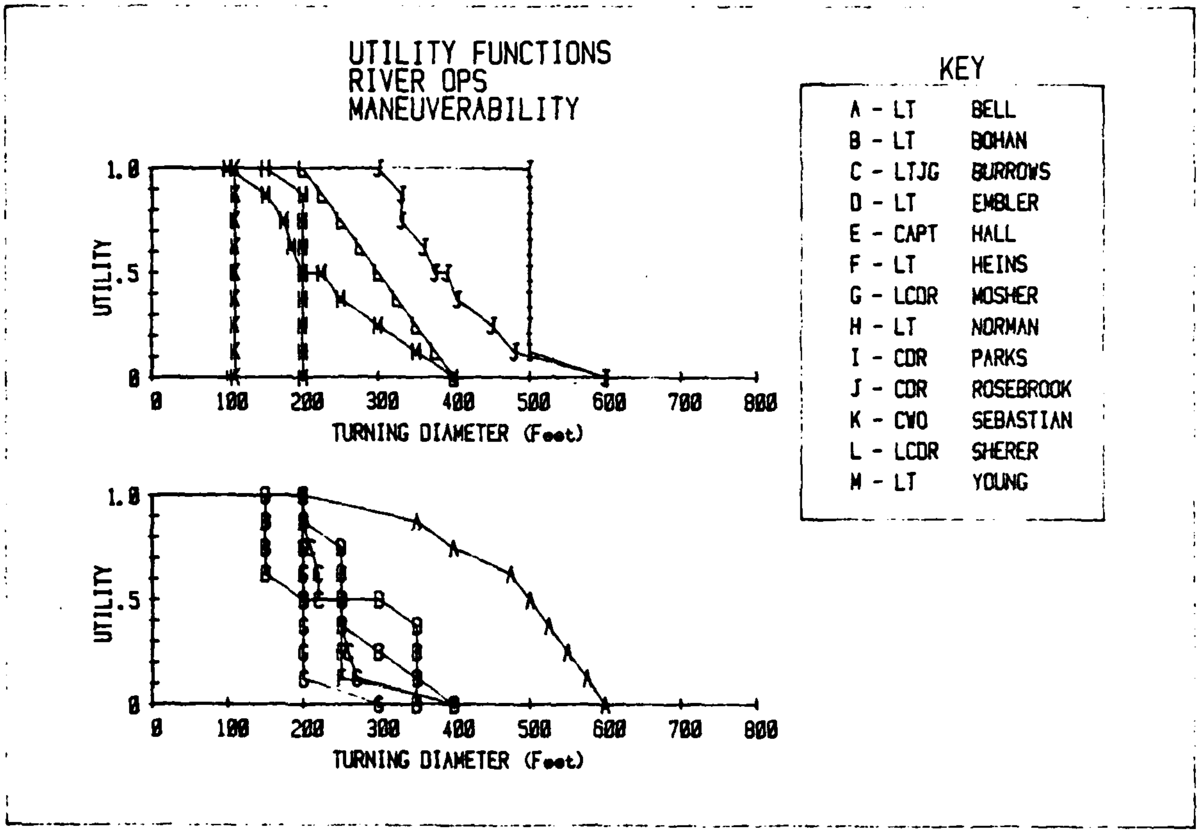

UTILITY FUNCTIONS
RESPONSE (OW)
MANEUVERABILITY
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 100 200 300 400 500 600 700 800
TURNING DIAMETER (Feet)
UTILITY
1.0
.5
0
0 100 200 300 400 500 600 700 800
TURNING DIAMETER (Feet)

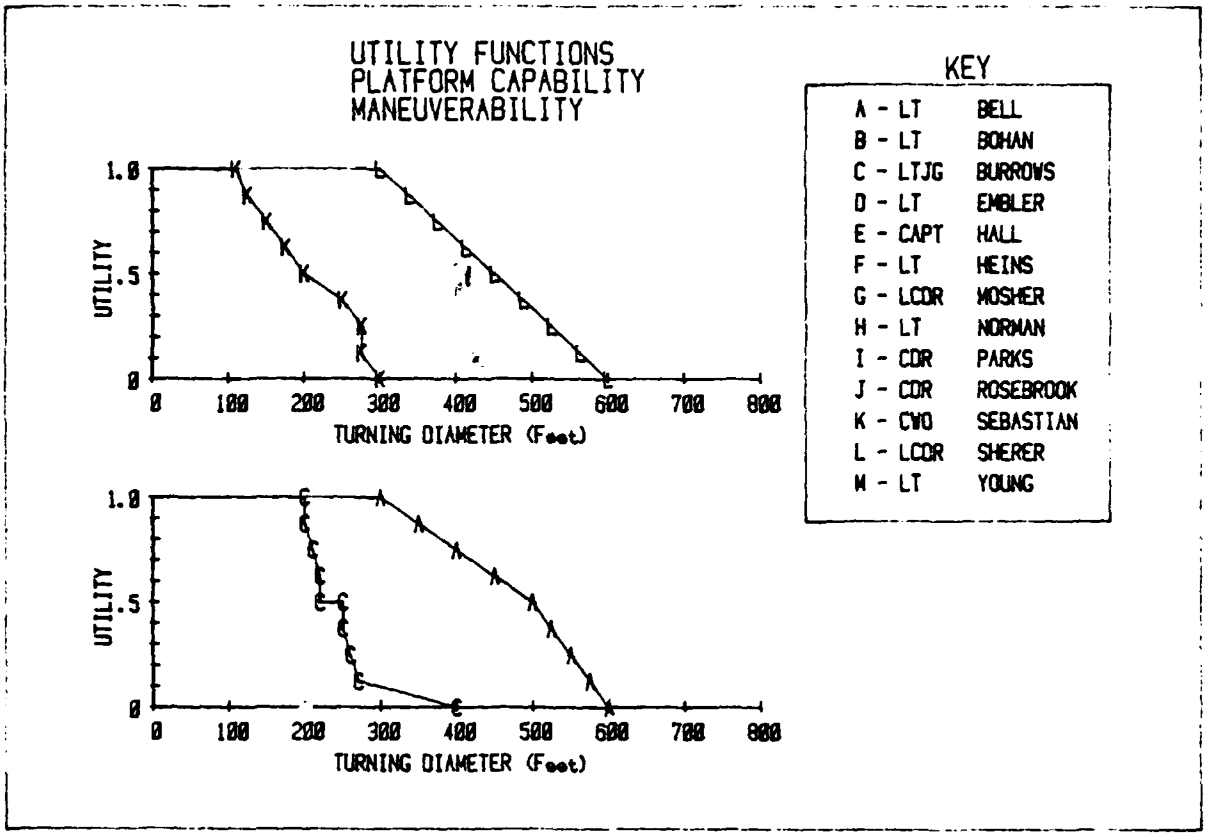


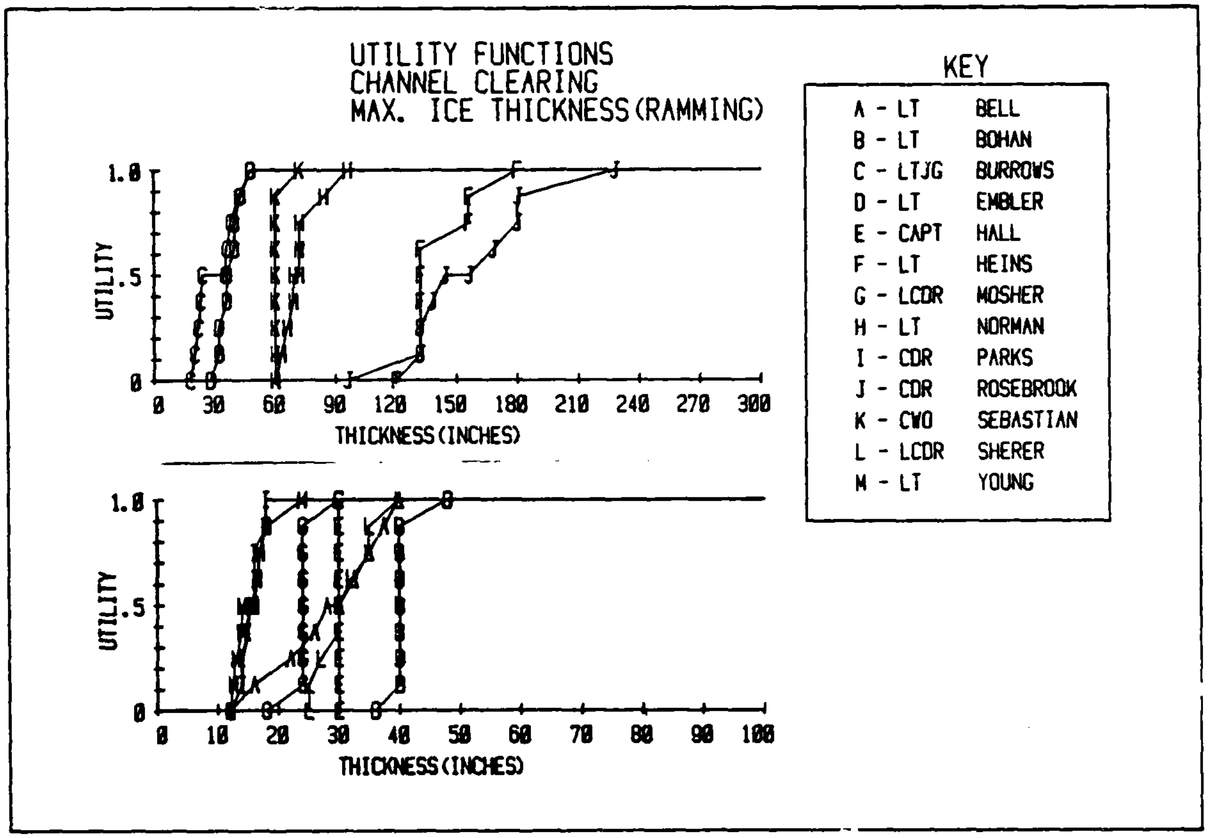
UTILITY FUNCTIONS
RESPONSE (FIELD)
MANEUVERABILITY
UTILITY
TURNING DIAMETER (Feet)
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG

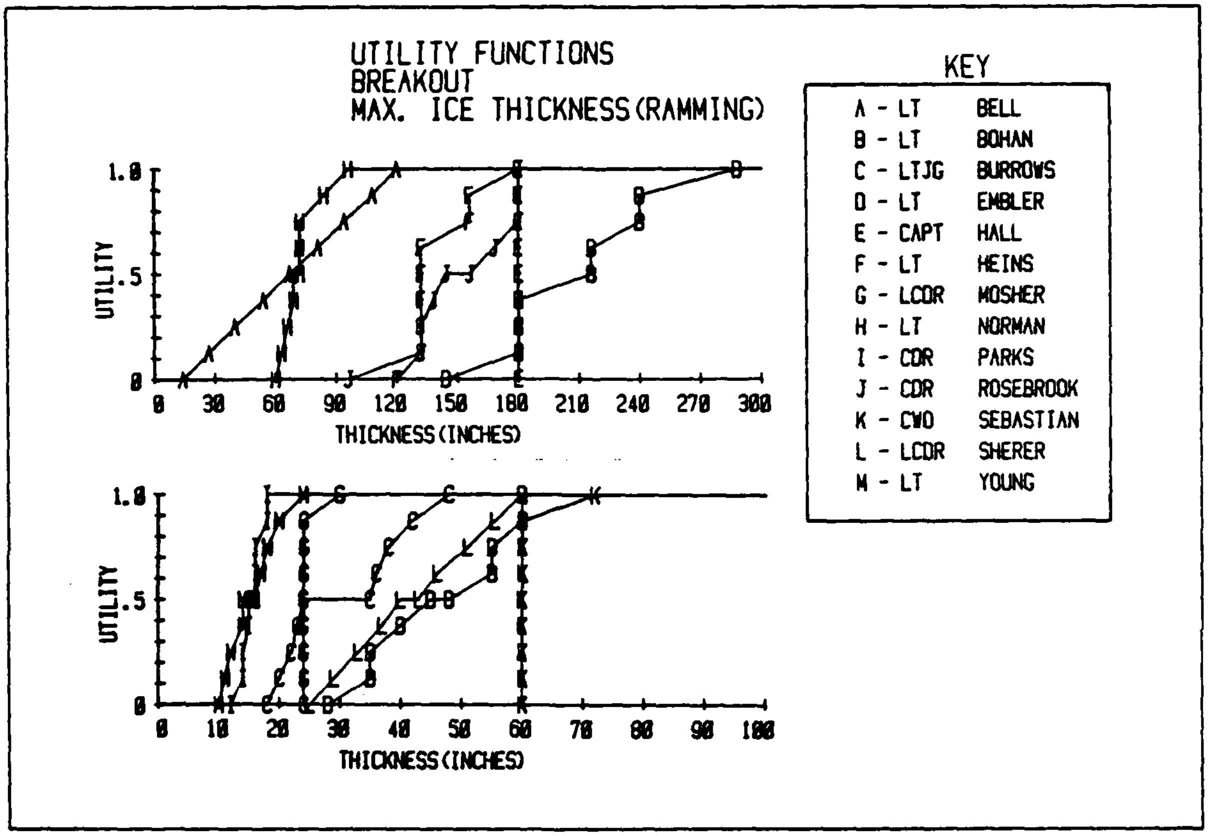


UTILITY FUNCTIONS
RESPONSE (BRASH)
MANEUVERABILITY
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
TURNING DIAMETER (Feet)

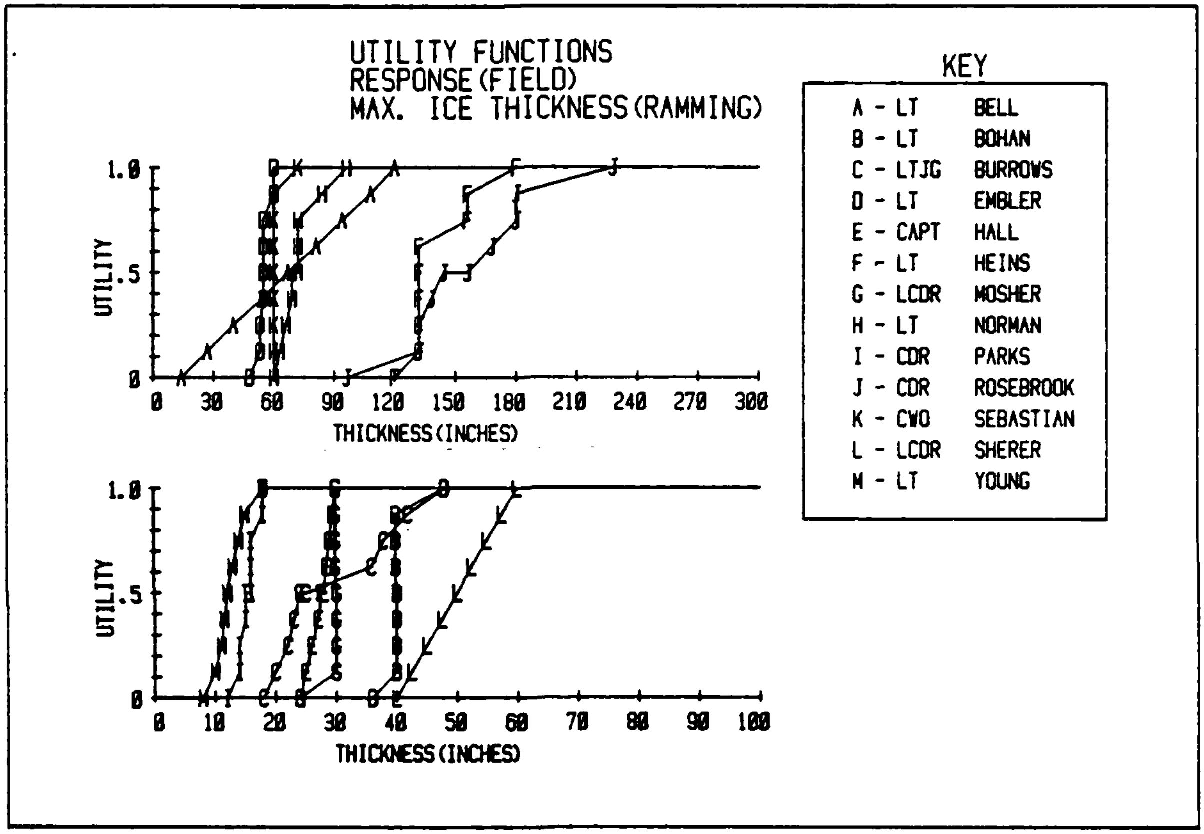

UTILITY FUNCTIONS
RIVER OPS
MANEUVERABILITY
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 100 200 300 400 500 600 700 800
TURNING DIAMETER (Feet)


UTILITY FUNCTIONS
PLATFORM CAPABILITY
MANEUVERABILITY
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 100 200 300 400 500 600 700 800
TURNING DIAMETER (Feet)
UTILITY
1.0
.5
0
0 100 200 300 400 500 600 700 800
TURNING DIAMETER (Feet)

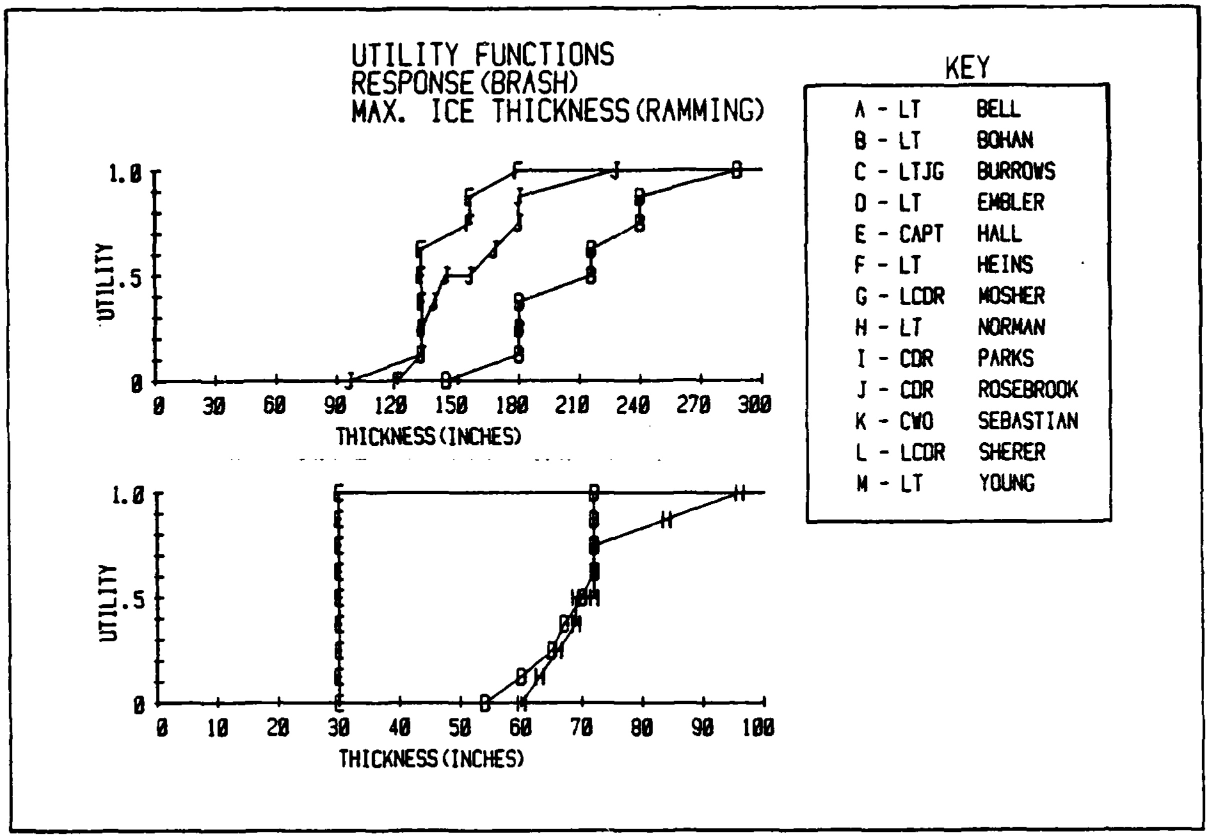

UTILITY FUNCTIONS
CHANNEL CLEARING
MAX. ICE THICKNESS (RAMMING)
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 30 60 90 120 150 180 210 240 270 300
THICKNESS (INCHES)
0 10 20 30 40 50 60 70 80 90 100
THICKNESS (INCHES)



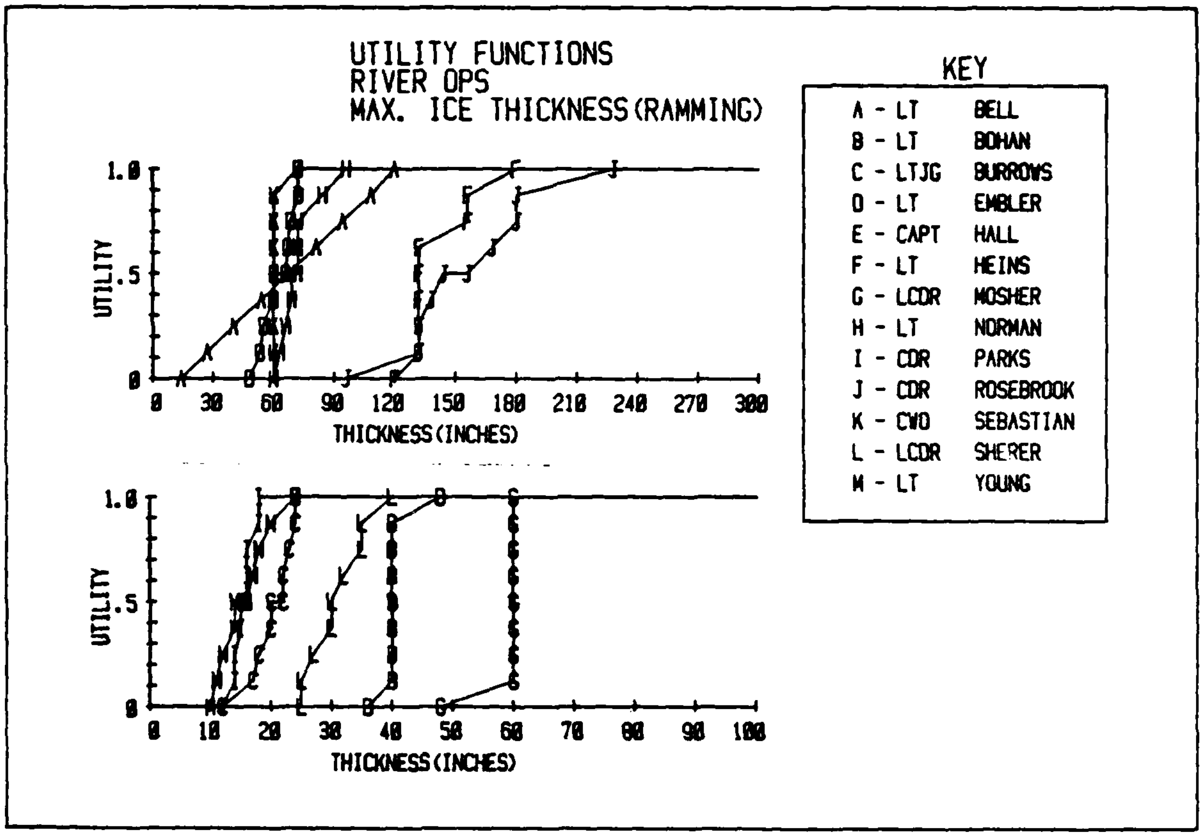
UTILITY FUNCTIONS
BREAKOUT
MAX. ICE THICKNESS (RAMMING)
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
THICKNESS (INCHES)

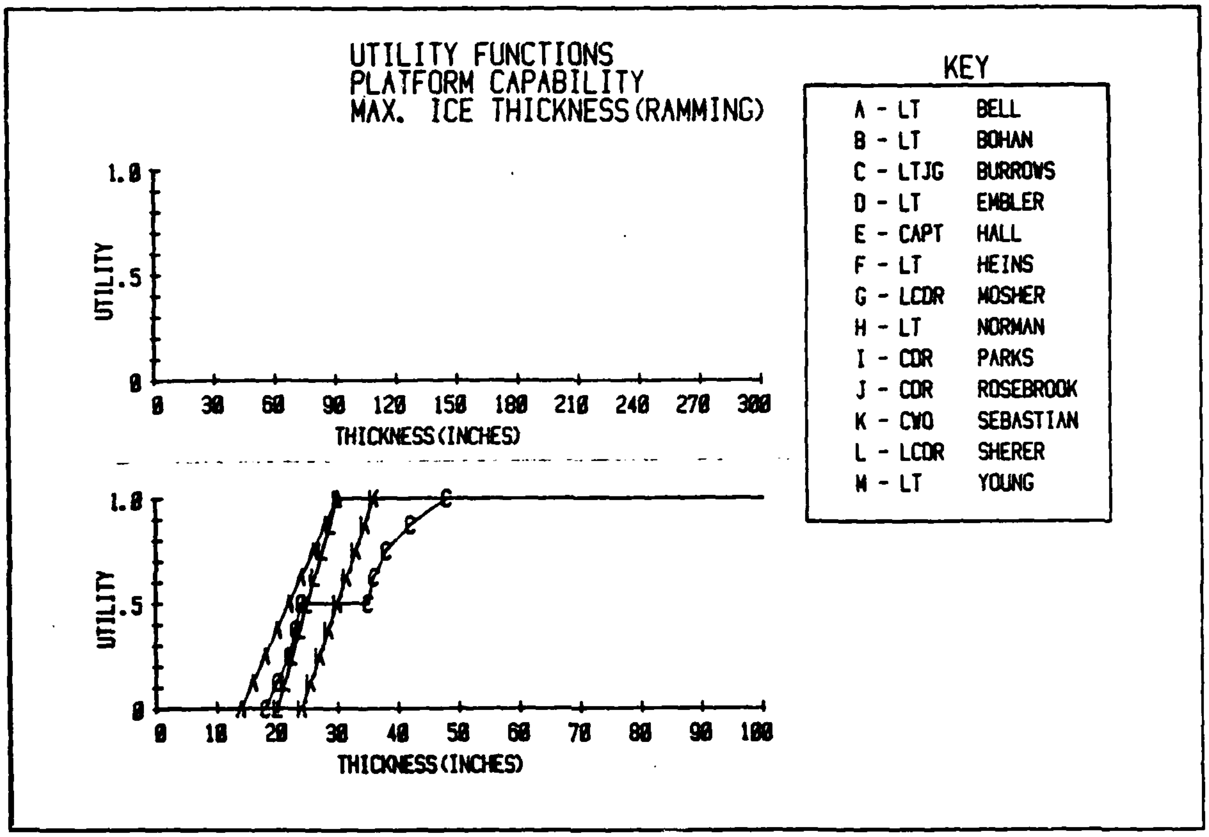


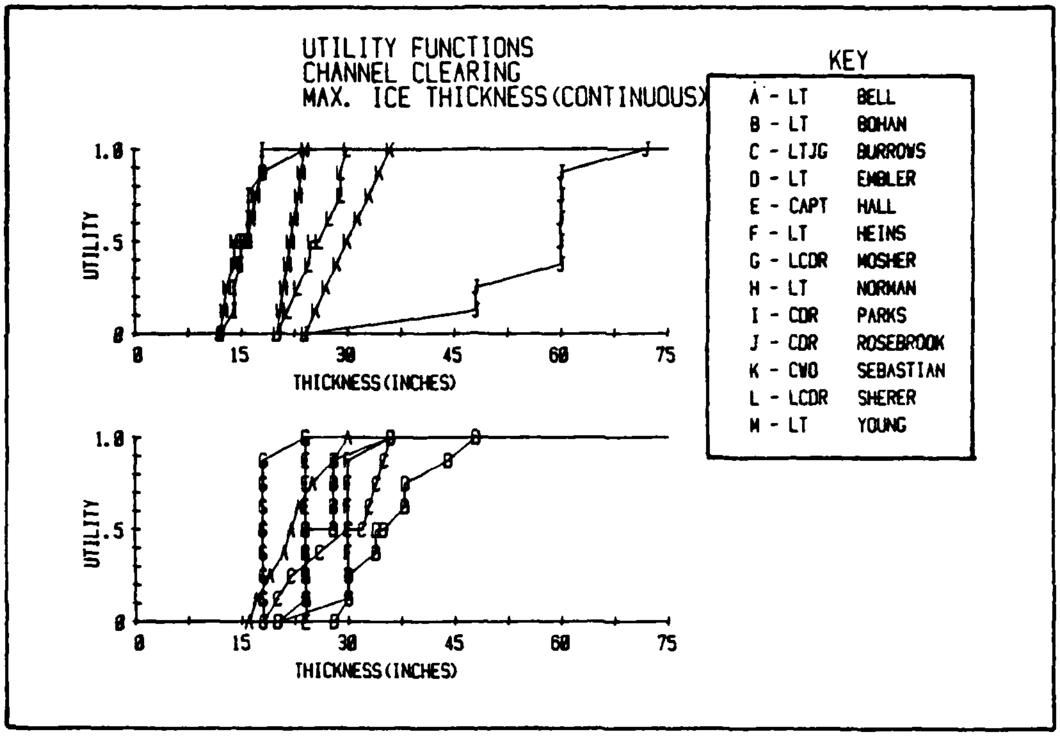
UTILITY FUNCTIONS
RESPONSE (FIELD)
MAX. ICE THICKNESS (RAMMING)
UTILITY
1.0
.5
0
0 30 60 90 120 150 180 210 240 270 300
THICKNESS (INCHES)
UTILITY
1.0
.5
0
0 10 20 30 40 50 60 70 80 90 100
THICKNESS (INCHES)
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG



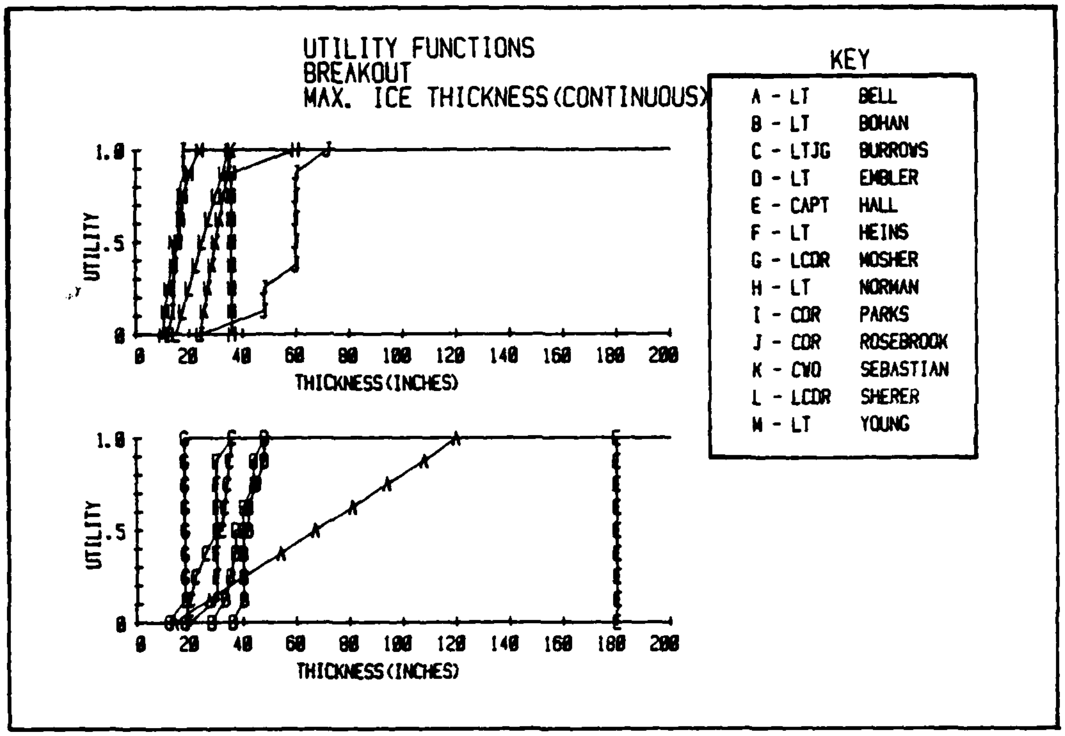
UTILITY FUNCTIONS
RESPONSE (BRASH)
MAX. ICE THICKNESS (RAMMING)
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
THICKNESS (INCHES)
UTILITY
THICKNESS (INCHES)

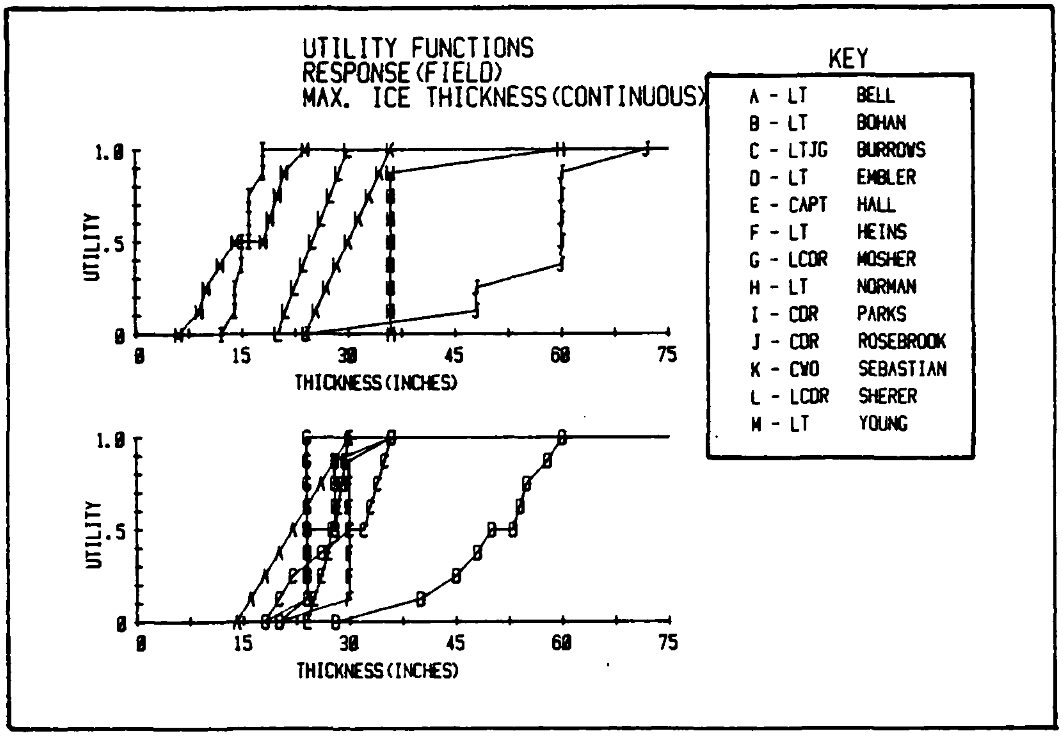

UTILITY FUNCTIONS
RIVER OPS
MAX. ICE THICKNESS (RAMMING)
UTILITY
THICKNESS (INCHES)
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG

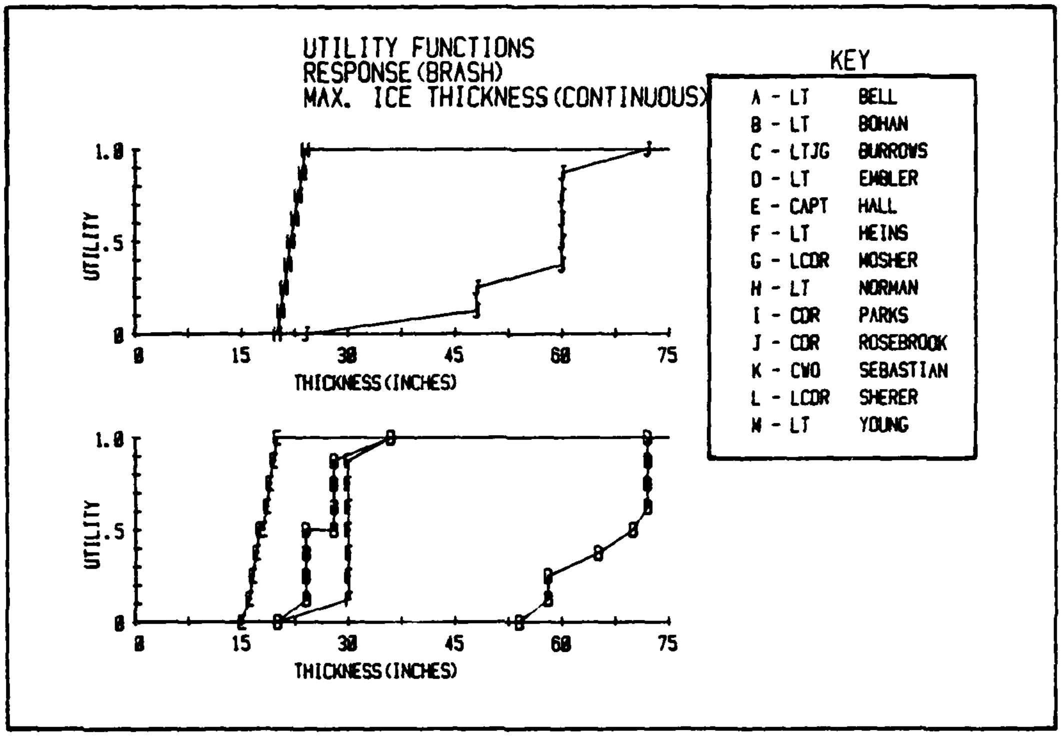

UTILITY FUNCTIONS
PLATFORM CAPABILITY
MAX. ICE THICKNESS (RAMMING)
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 30 60 90 120 150 180 210 240 270 300
THICKNESS (INCHES)
UTILITY
1.0
.5
0
0 10 20 30 40 50 60 70 80 90 100
THICKNESS (INCHES)

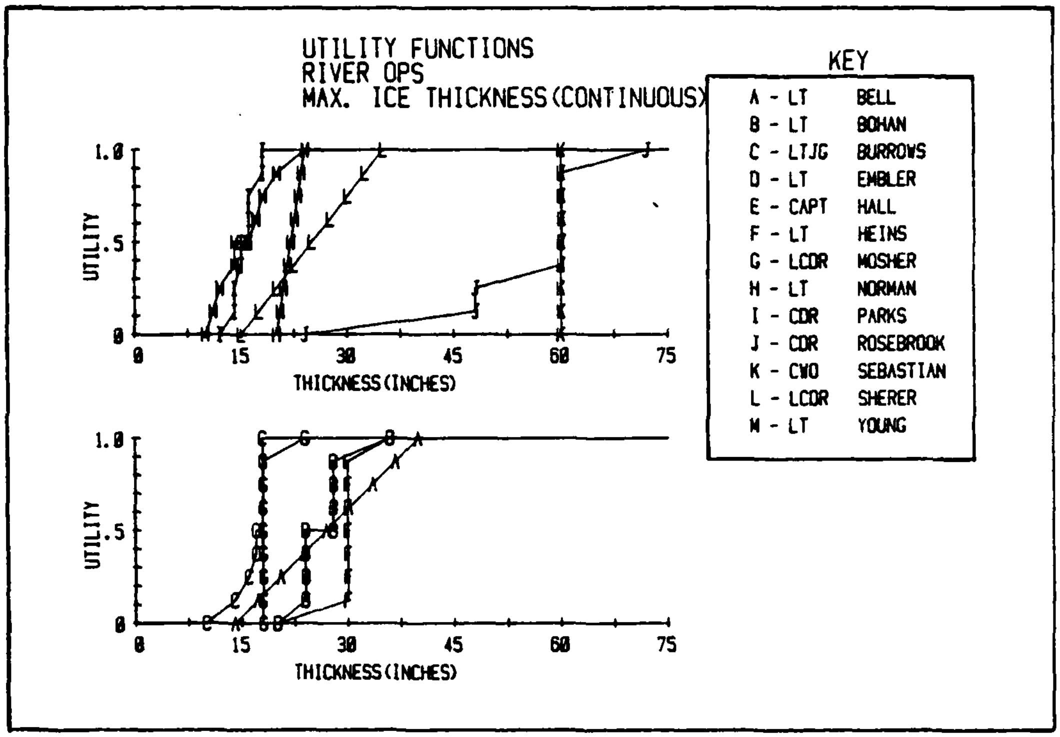


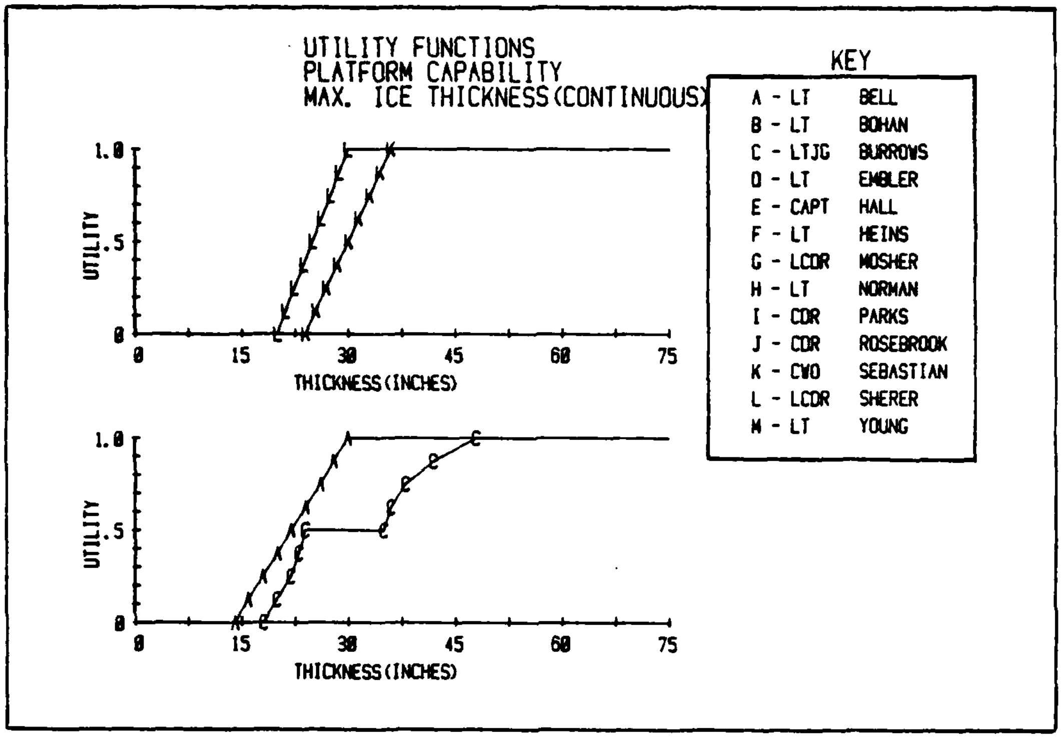
UTILITY FUNCTIONS
CHANNEL CLEARING
MAX. ICE THICKNESS(CONTINUOUS)
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
THICKNESS(INCHES)

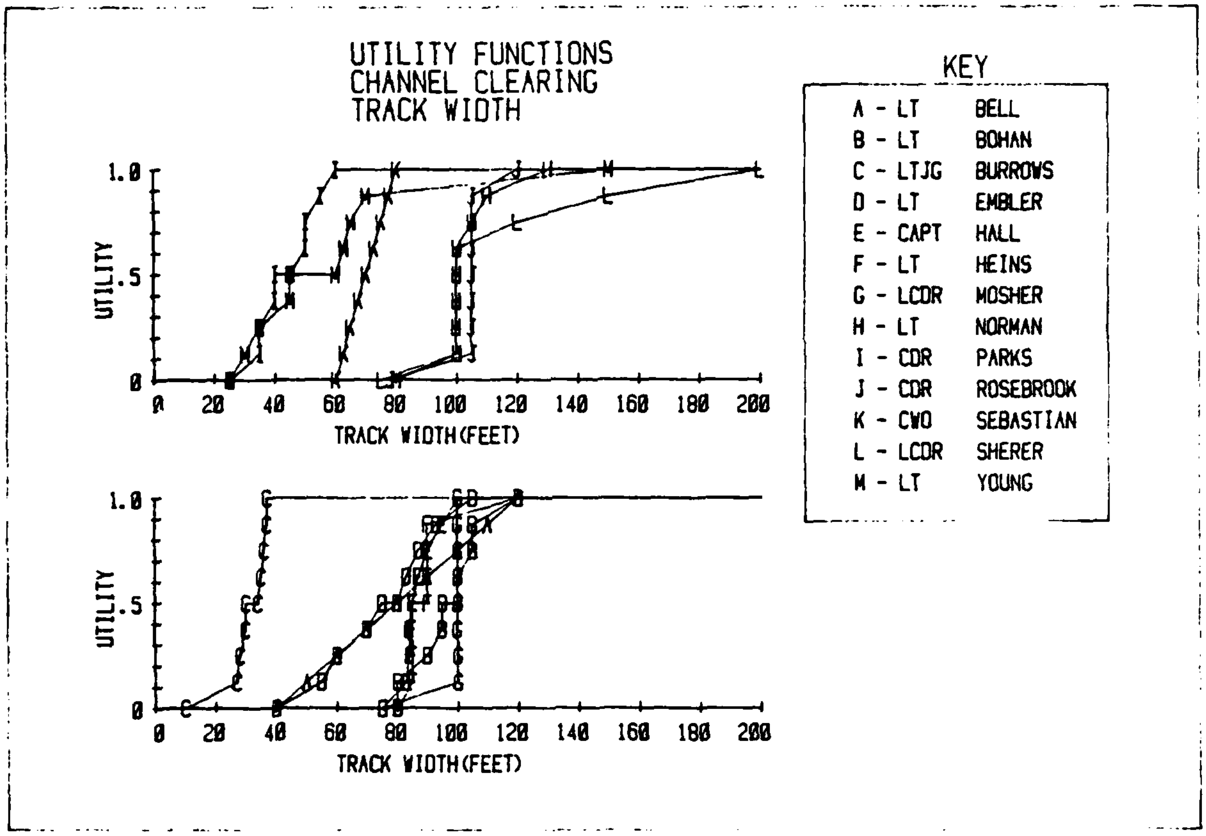

UTILITY FUNCTIONS
BREAKOUT
MAX. ICE THICKNESS (CONTINUOUS)
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
THICKNESS (INCHES)
UTILITY
THICKNESS (INCHES)

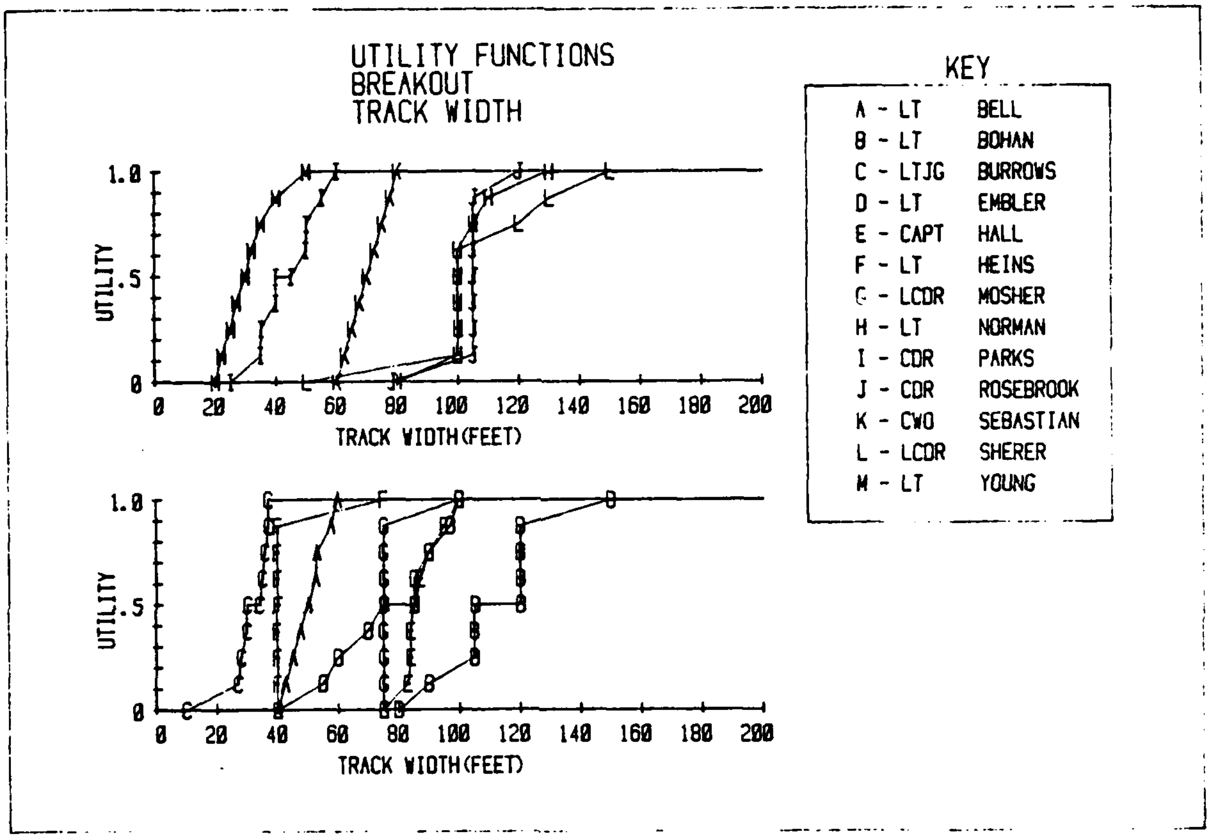

UTILITY FUNCTIONS
RESPONSE(FIELD)
MAX. ICE THICKNESS(CONTINUOUS)
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 15 30 45 60 75
THICKNESS(INCHES)
UTILITY
1.0
.5
0
0 15 30 45 60 75
THICKNESS(INCHES)


UTILITY FUNCTIONS
RESPONSE (BRASH)
MAX. ICE THICKNESS (CONTINUOUS)
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
THICKNESS (INCHES)
1.0
.5
0
15
30
45
60
75

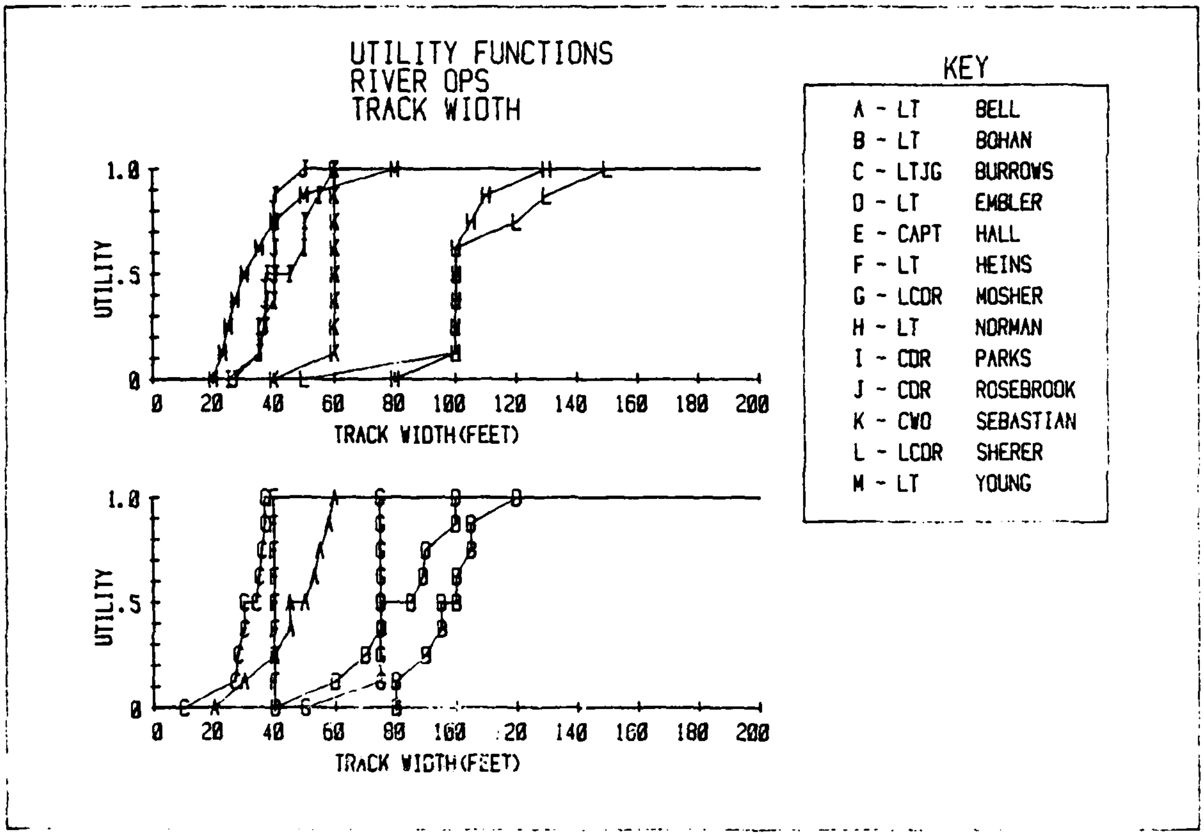

UTILITY FUNCTIONS
RIVER OPS
MAX. ICE THICKNESS (CONTINUOUS)
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
THICKNESS (INCHES)
1.0
.5
0
15
30
45
60
75

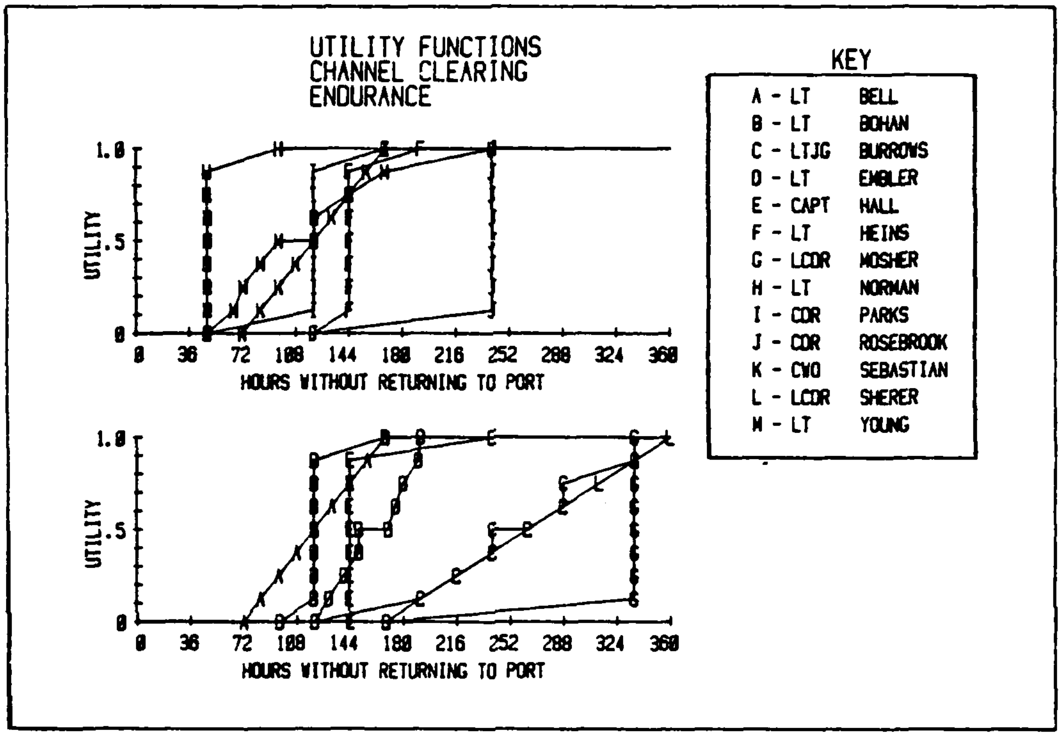

UTILITY FUNCTIONS
PLATFORM CAPABILITY
MAX. ICE THICKNESS (CONTINUOUS)
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0
15
30
45
60
75
THICKNESS (INCHES)
UTILITY
1.0
.5
0
0
15
30
45
60
75
THICKNESS (INCHES)


UTILITY FUNCTIONS
CHANNEL CLEARING
TRACK WIDTH
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 20 40 60 80 100 120 140 160 180 200
TRACK WIDTH (FEET)

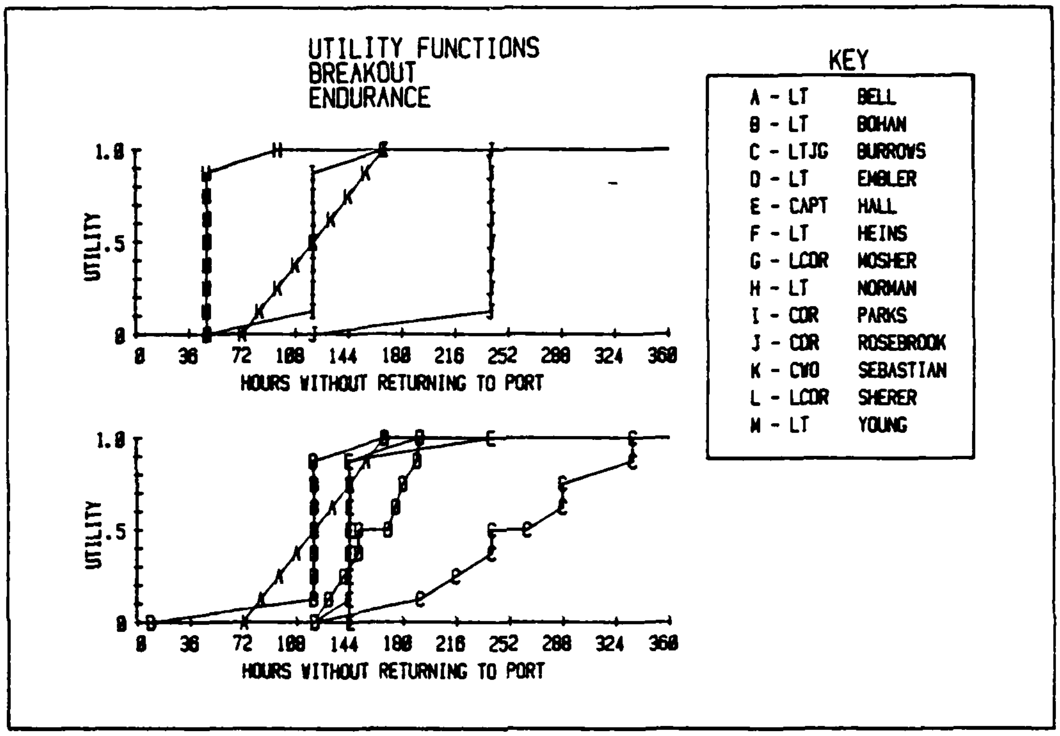


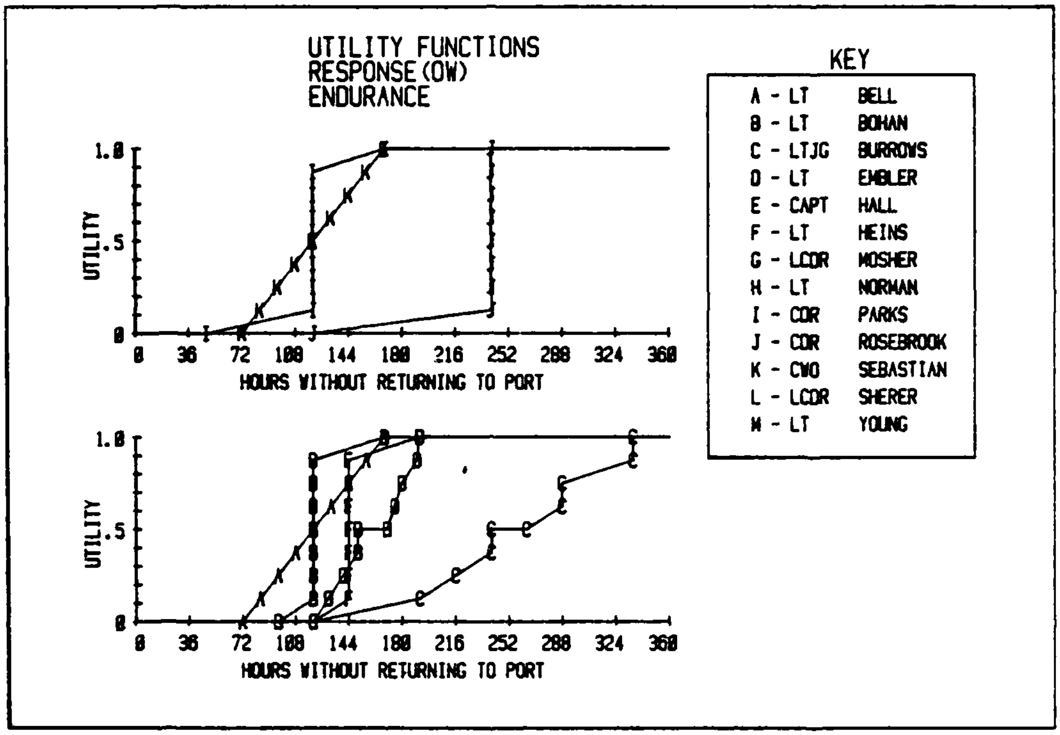
UTILITY FUNCTIONS
BREAKOUT
TRACK WIDTH
UTILITY
1.0
.5
0
0 20 40 60 80 100 120 140 160 180 200
TRACK WIDTH (FEET)
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG

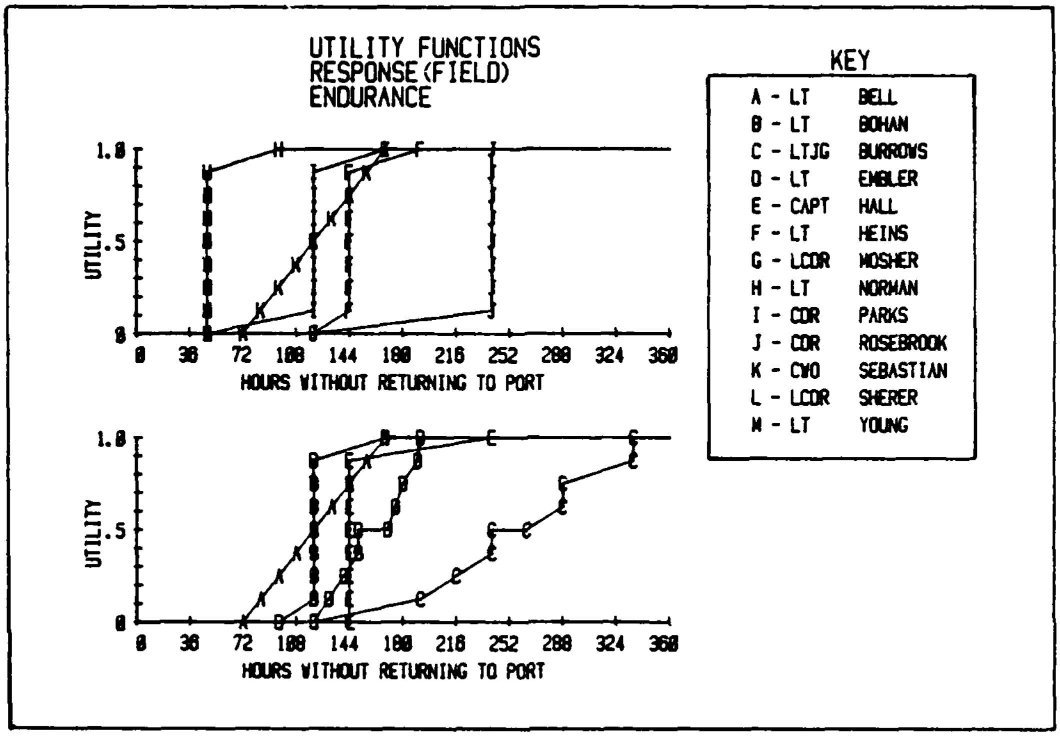

UTILITY FUNCTIONS
RIVER OPS
TRACK WIDTH
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
TRACK WIDTH (FEET)
0
.5
1.0
0 20 40 60 80 100 120 140 160 180 200

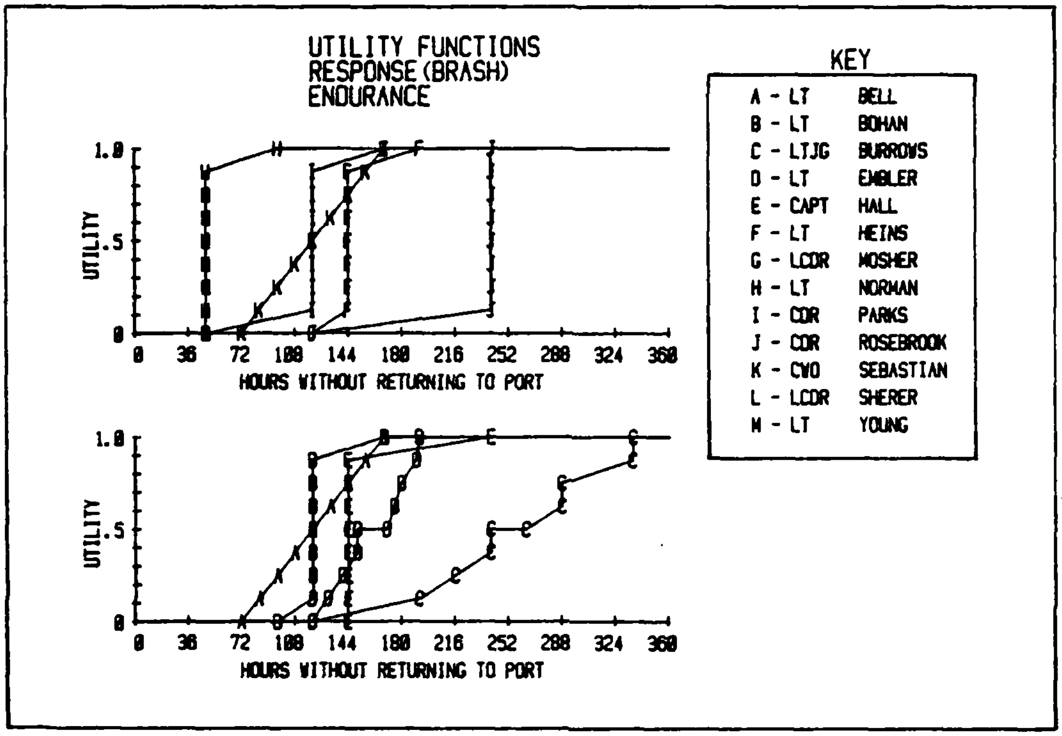


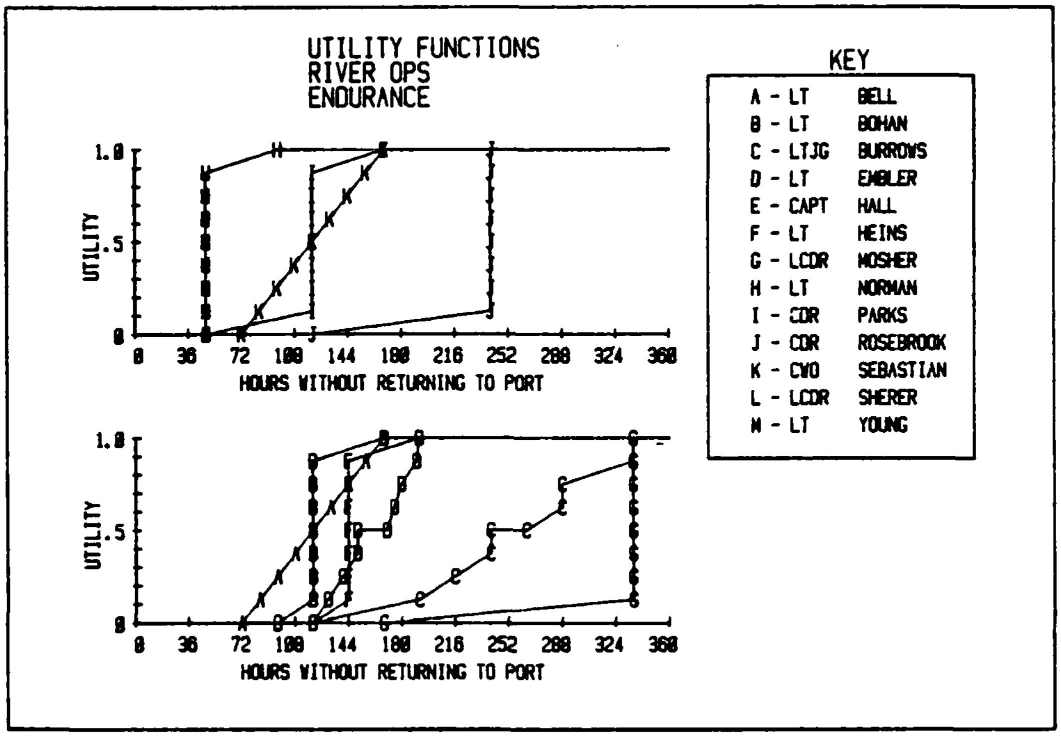
UTILITY FUNCTIONS
CHANNEL CLEARING
ENDURANCE
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
HOURS WITHOUT RETURNING TO PORT
UTILITY
HOURS WITHOUT RETURNING TO PORT

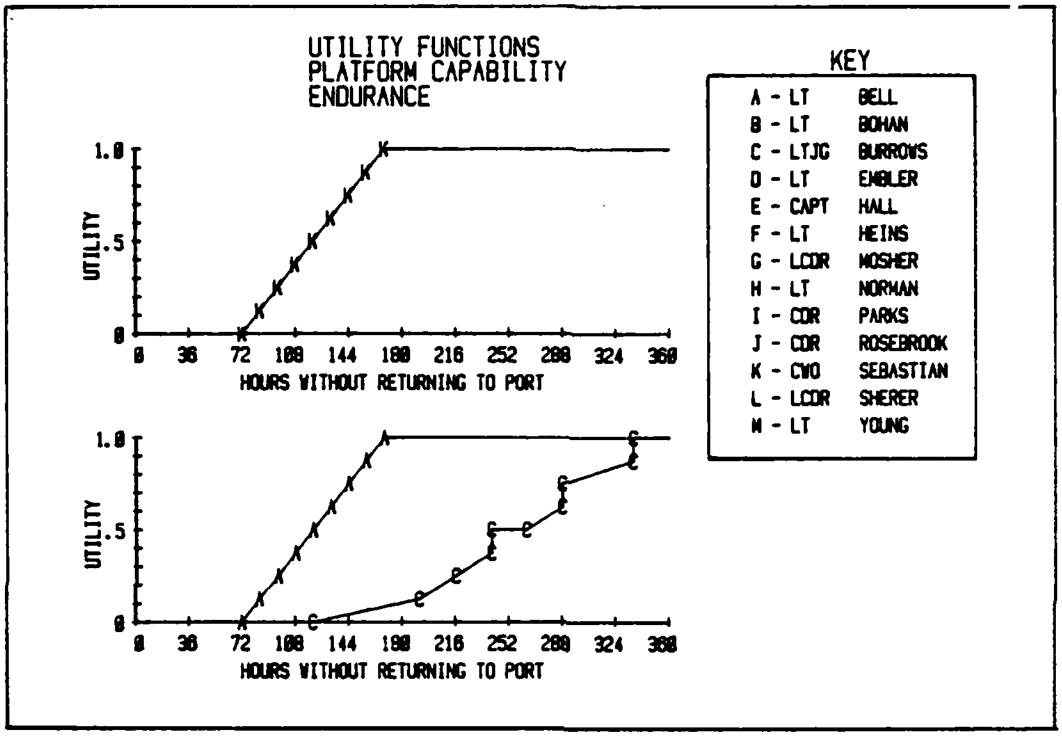

UTILITY FUNCTIONS
BREAKOUT
ENDURANCE
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 36 72 108 144 180 216 252 288 324 360
HOURS WITHOUT RETURNING TO PORT
UTILITY
1.0
.5
0
0 36 72 108 144 180 216 252 288 324 360
HOURS WITHOUT RETURNING TO PORT


UTILITY FUNCTIONS
RESPONSE (OW)
ENDURANCE
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
HOURS WITHOUT RETURNING TO PORT
0 36 72 108 144 180 216 252 288 324 360
1.0
.5
0

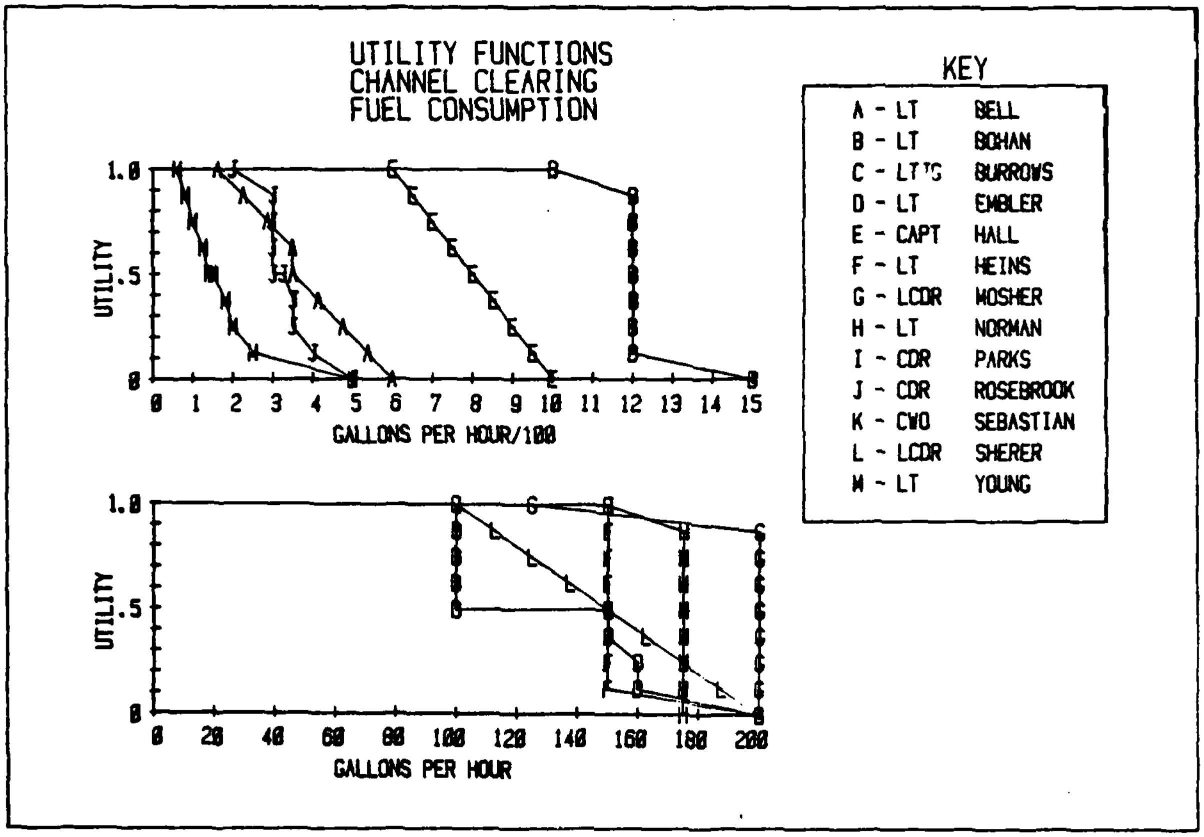

UTILITY FUNCTIONS
RESPONSE (FIELD)
ENDURANCE
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
HOURS WITHOUT RETURNING TO PORT
0 36 72 108 144 180 216 252 288 324 360
1.0
.5
0

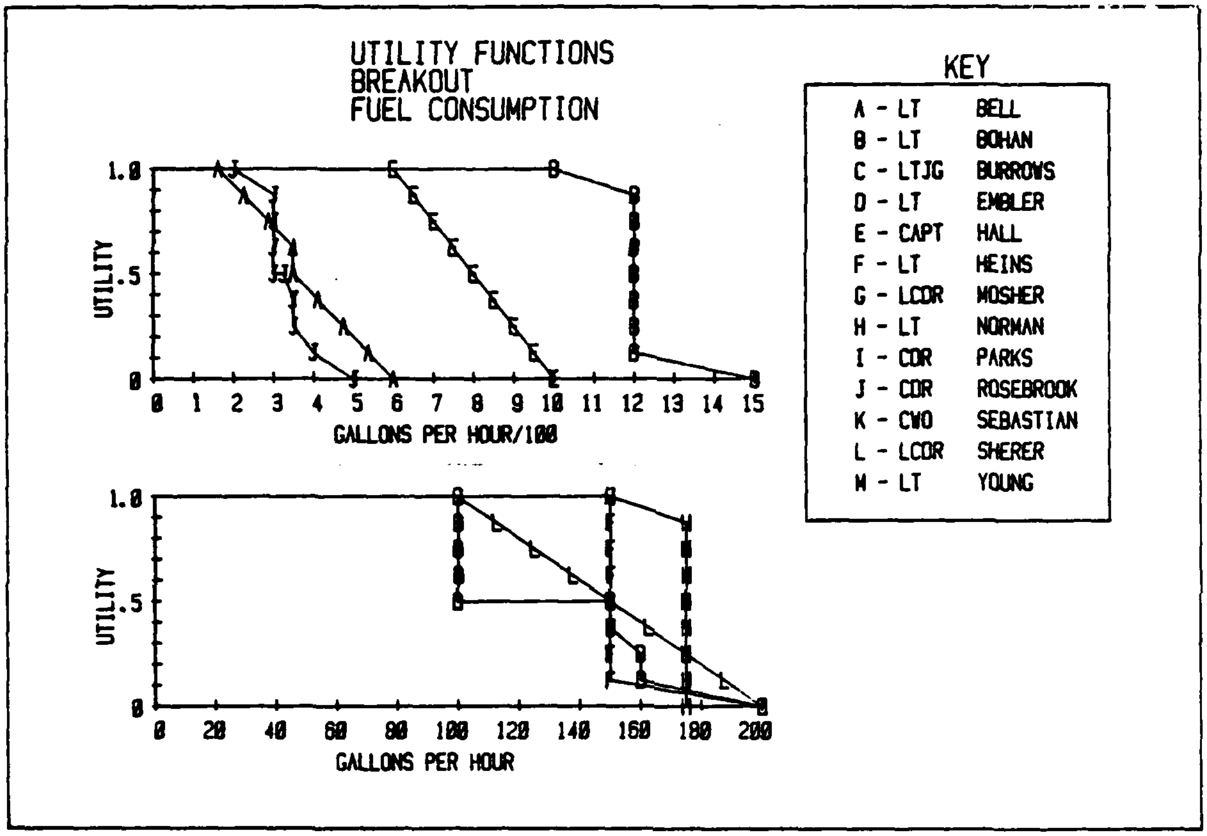

UTILITY FUNCTIONS
RESPONSE (BRASH)
ENDURANCE
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 36 72 108 144 180 216 252 288 324 360
HOURS WITHOUT RETURNING TO PORT


UTILITY FUNCTIONS
RIVER OPS
ENDURANCE
UTILITY
1.0
.5
0
0 36 72 108 144 180 216 252 288 324 360
HOURS WITHOUT RETURNING TO PORT
UTILITY
1.0
.5
0
0 36 72 108 144 180 216 252 288 324 360
HOURS WITHOUT RETURNING TO PORT
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG

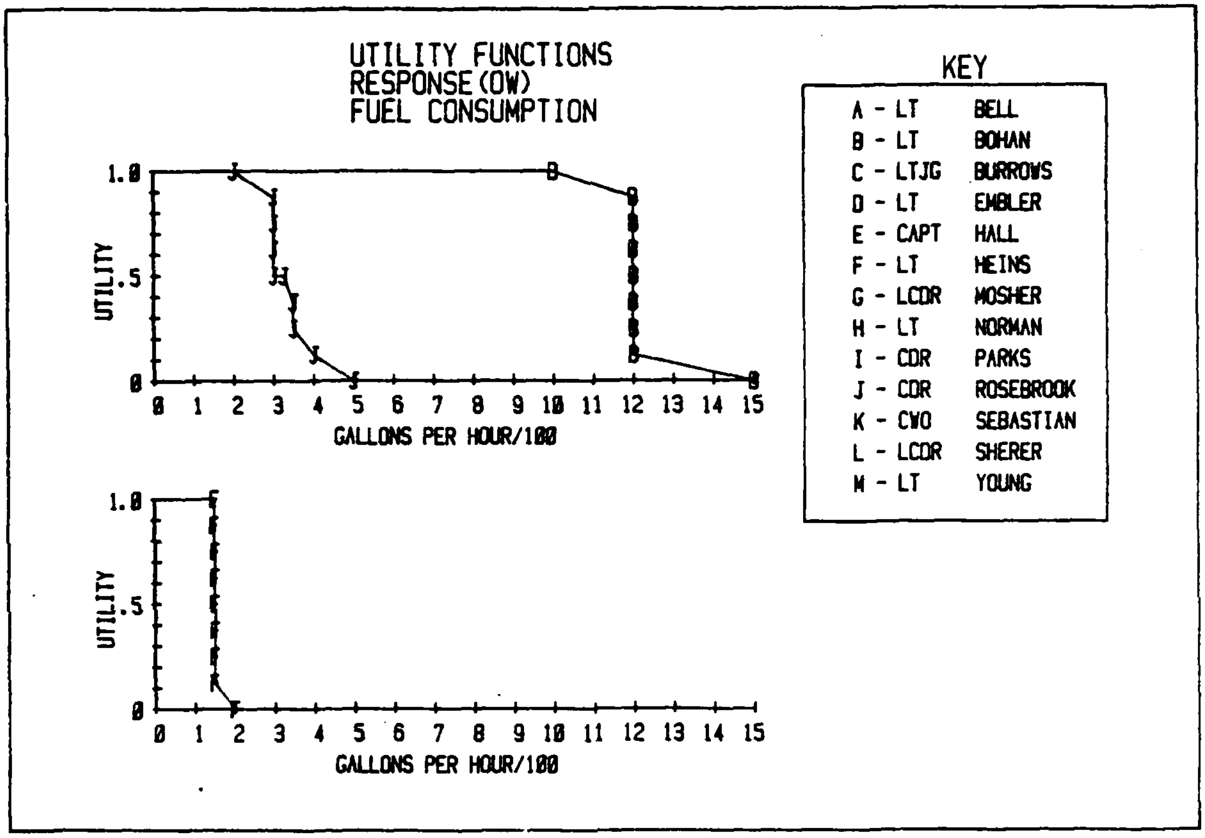


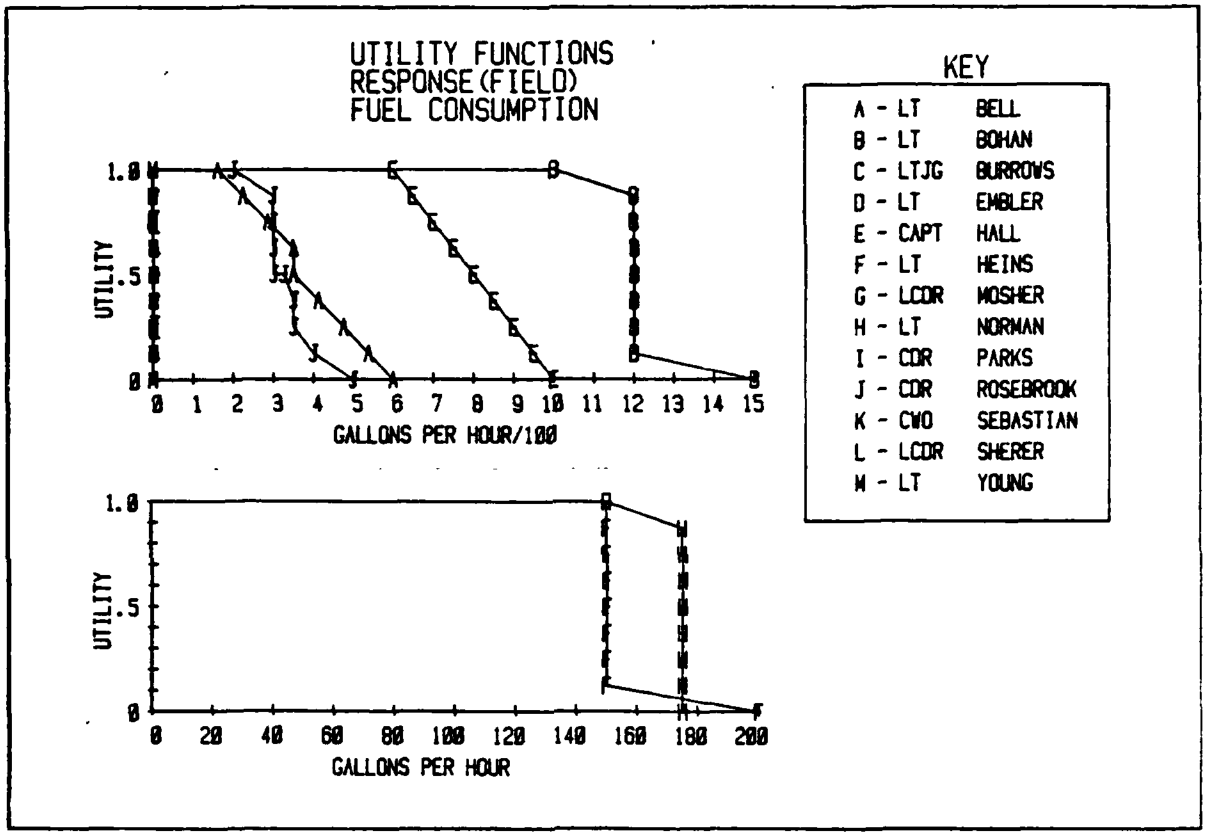
UTILITY FUNCTIONS
PLATFORM CAPABILITY
ENDURANCE
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 36 72 108 144 180 216 252 288 324 360
HOURS WITHOUT RETURNING TO PORT


UTILITY FUNCTIONS
CHANNEL CLEARING
FUEL CONSUMPTION
UTILITY
GALLONS PER HOUR/100
GALLONS PER HOUR
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG



UTILITY FUNCTIONS
BREAKOUT
FUEL CONSUMPTION
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
GALLONS PER HOUR/100
UTILITY
1.0
.5
0
0 20 40 60 80 100 120 140 160 180 200
GALLONS PER HOUR


UTILITY FUNCTIONS
RESPONSE (OW)
FUEL CONSUMPTION
UTILITY
1.0
.5
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
GALLONS PER HOUR/100
UTILITY
1.0
.5
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
GALLONS PER HOUR/100
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG


UTILITY FUNCTIONS
RESPONSE (FIELD)
FUEL CONSUMPTION
UTILITY
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GALLONS PER HOUR/100
UTILITY
1.0
.5
0
0 20 40 60 80 100 120 140 160 180 200
GALLONS PER HOUR
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
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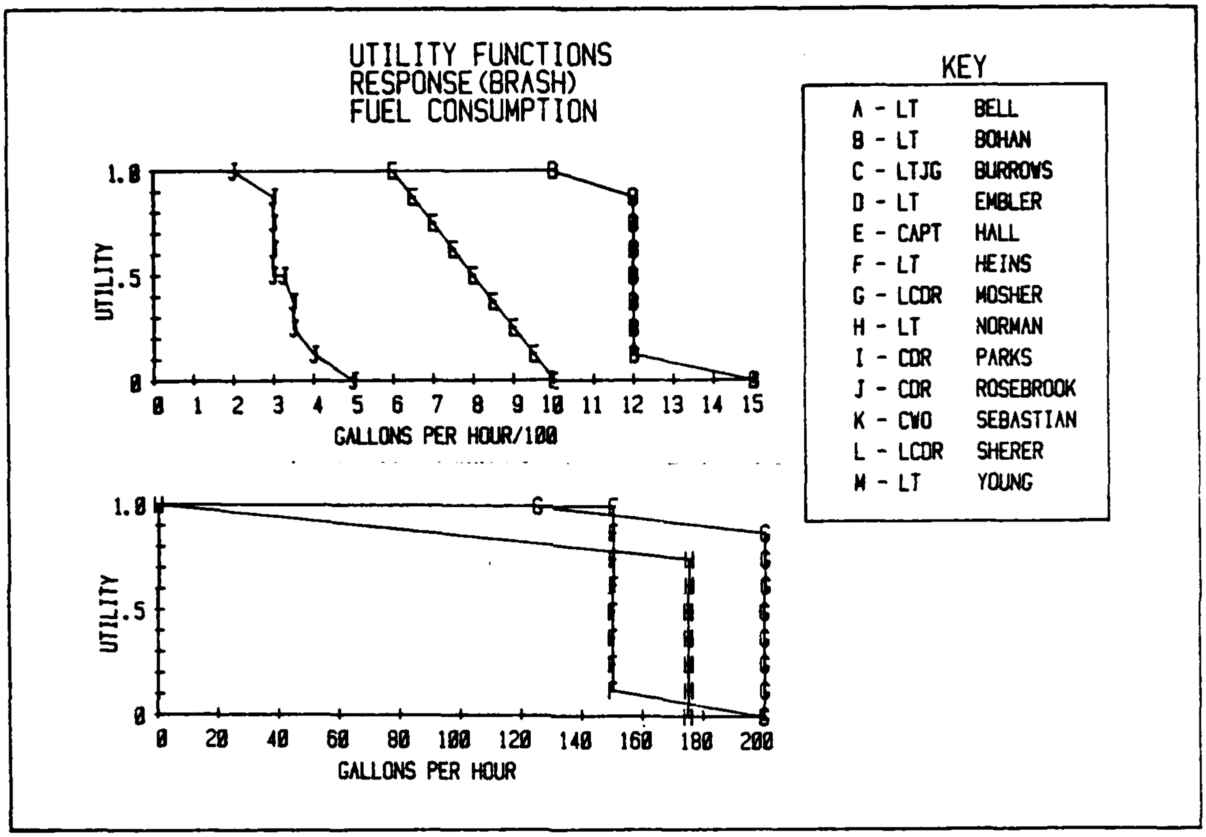
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG


UTILITY FUNCTIONS
RESPONSE (BRASH)
FUEL CONSUMPTION
KEY
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B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
GALLONS PER HOUR/100
UTILITY
1.0
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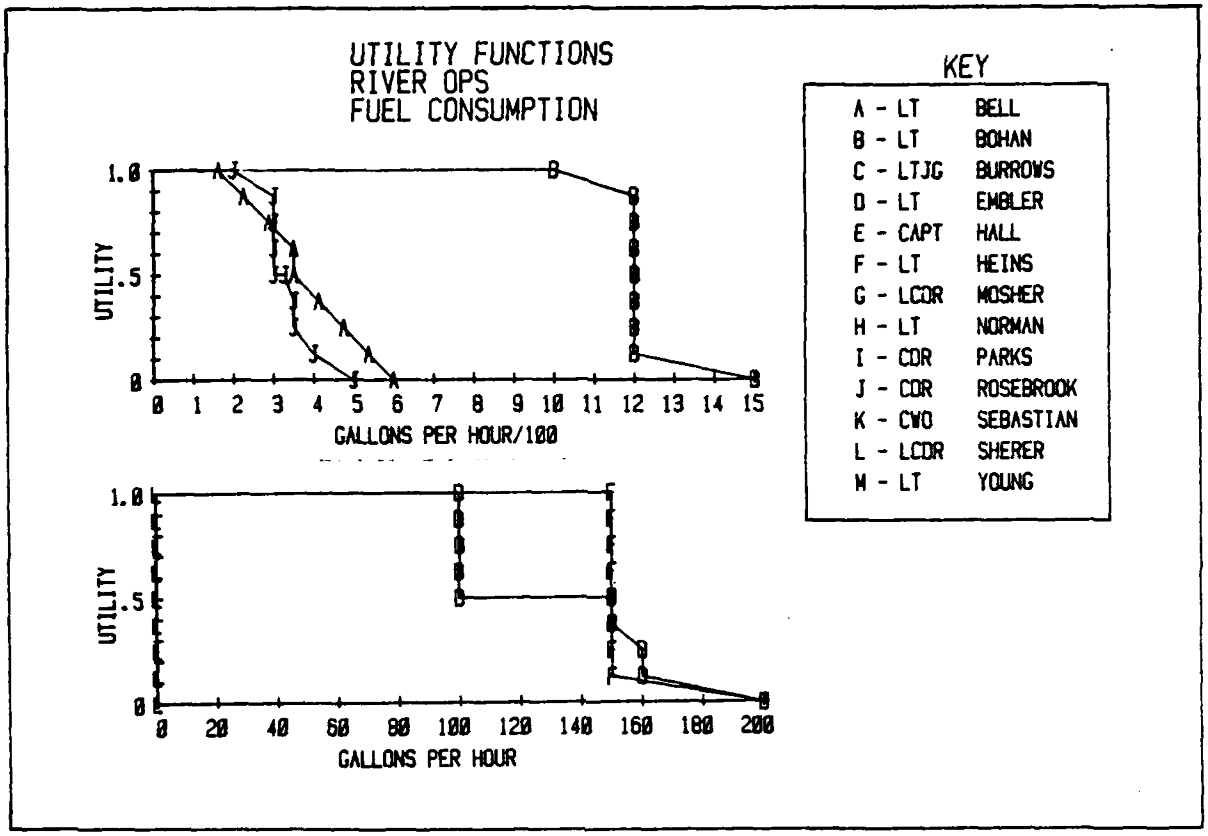
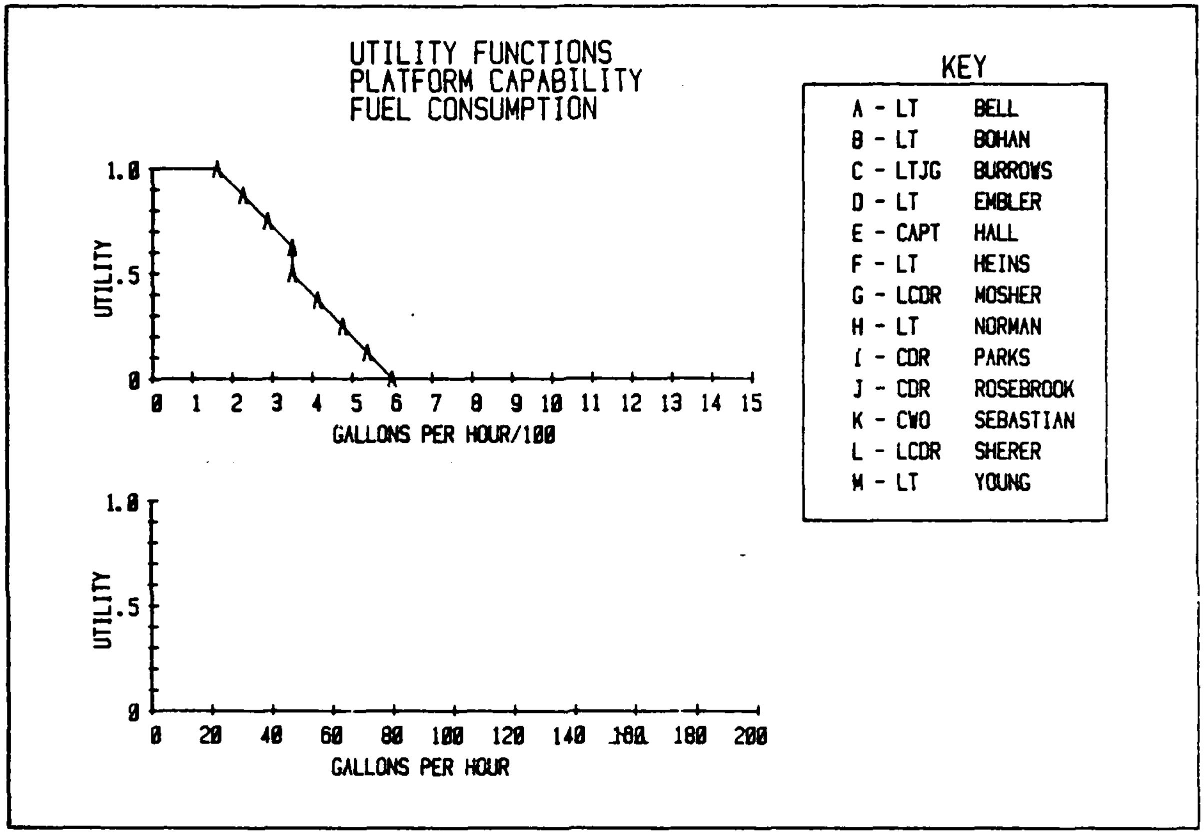
GALLONS PER HOUR


UTILITY FUNCTIONS
RIVER OPS
FUEL CONSUMPTION
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
GALLONS PER HOUR/100
GALLONS PER HOUR


UTILITY FUNCTIONS
PLATFORM CAPABILITY
FUEL CONSUMPTION
KEY
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B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
GALLONS PER HOUR/100
UTILITY
1.0
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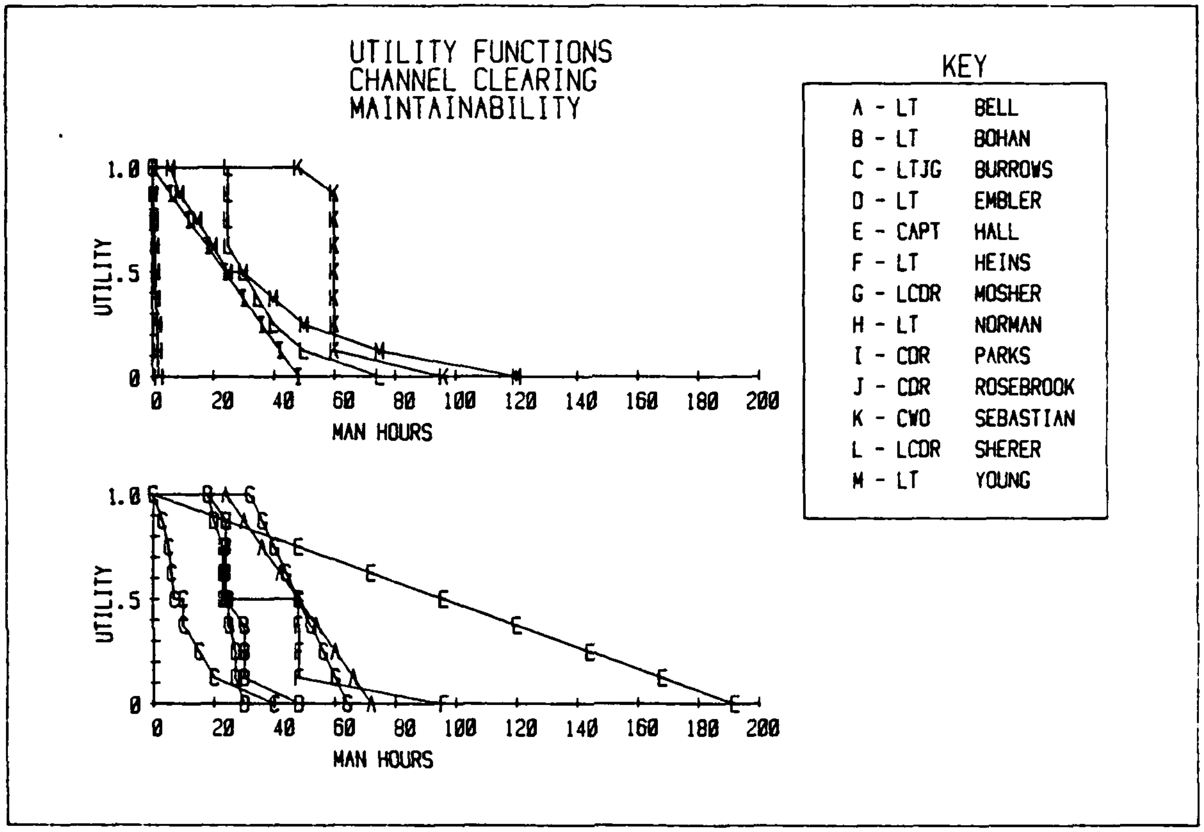
GALLONS PER HOUR


UTILITY FUNCTIONS
CHANNEL CLEARING
MAINTAINABILITY
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
MAN HOURS
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.5
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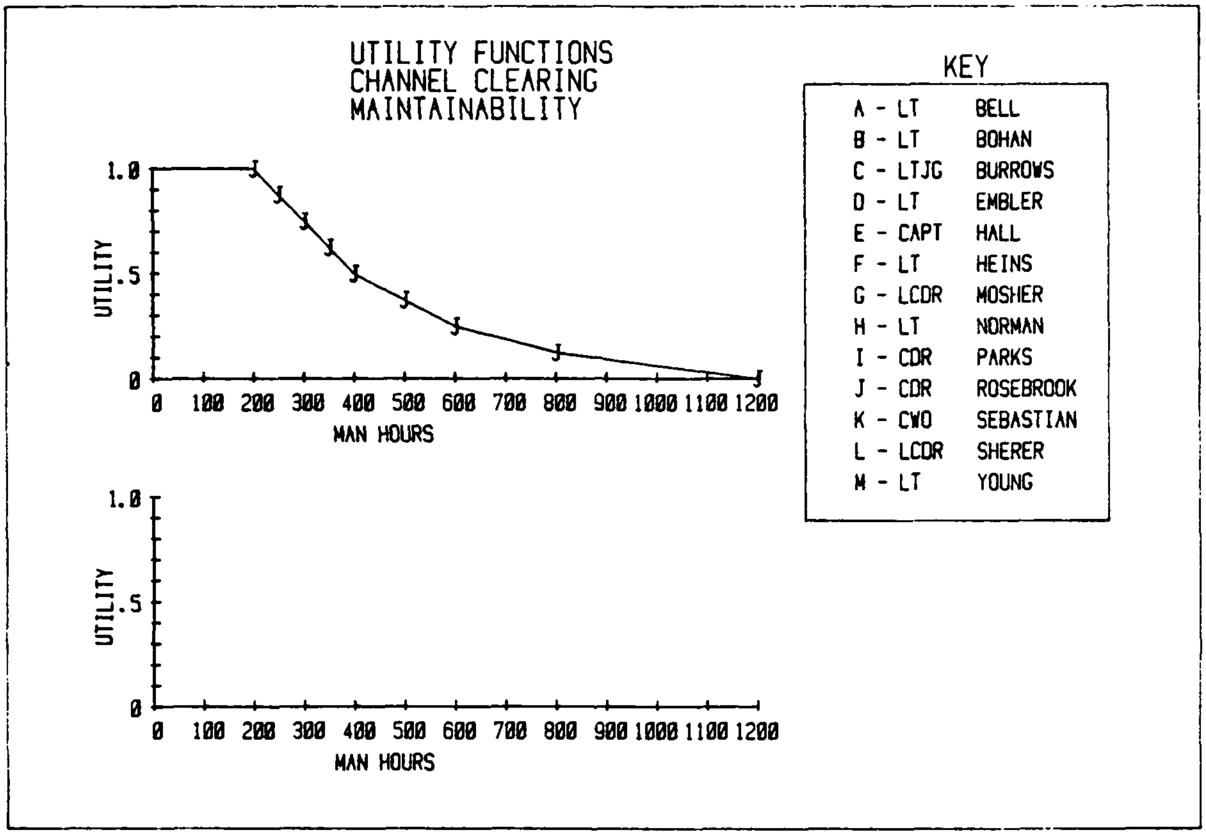

UTILITY FUNCTIONS
CHANNEL CLEARING
MAINTAINABILITY
KEY
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B - LT BOHAN
C - LTJG BURROWS
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F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
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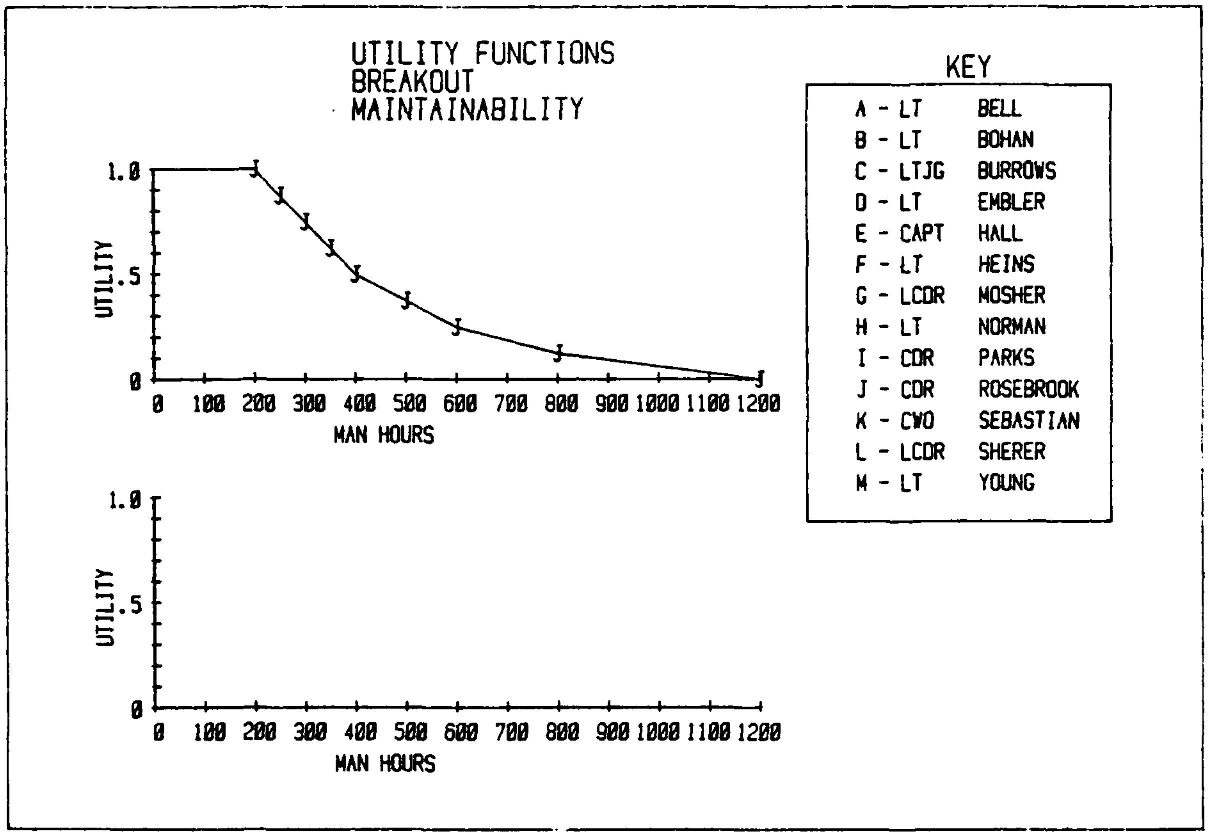
MAN HOURS
UTILITY
1.0
.5
0
0 100 200 300 400 500 600 700 800 900 1000 1100 1200
MAN HOURS



UTILITY FUNCTIONS
BREAKOUT
MAINTAINABILITY
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UTILITY .5
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MAN HOURS
1.0
UTILITY .5
0
0 100 200 300 400 500 600 700 800 900 1000 1100 1200
MAN HOURS
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
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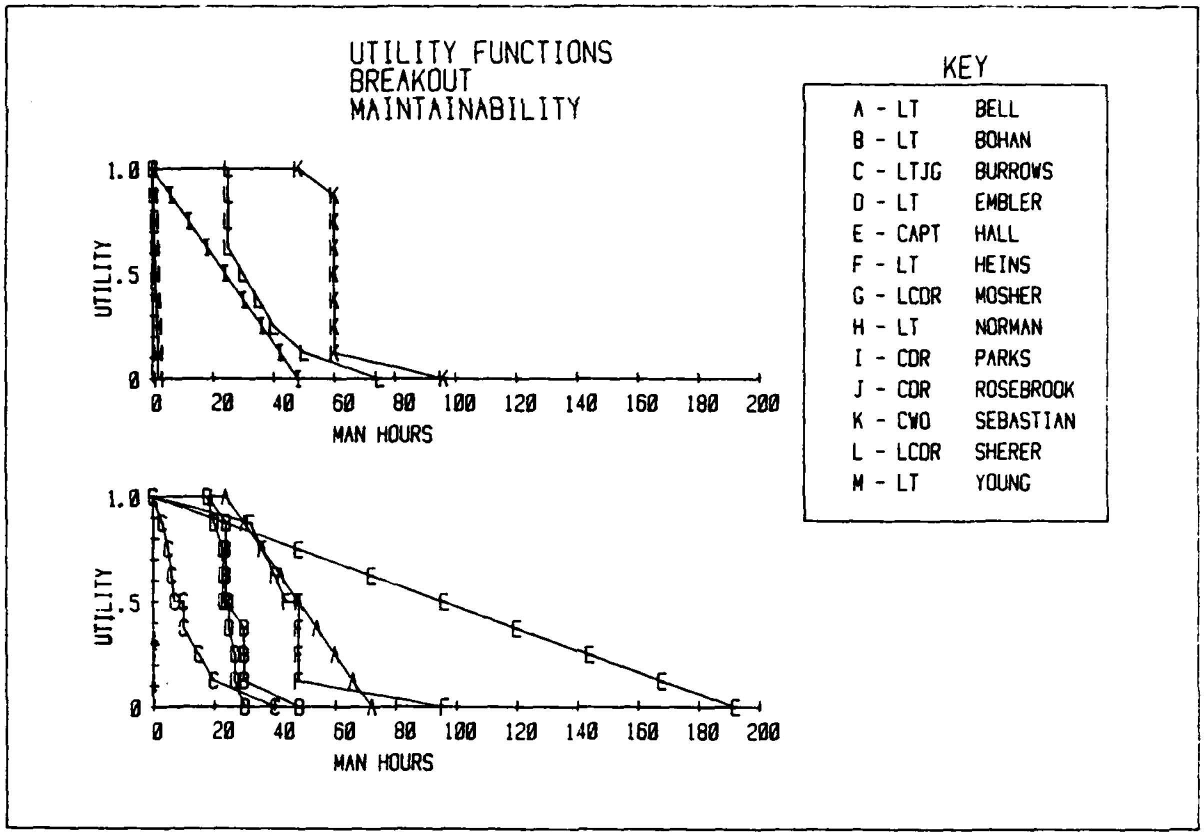
UTILITY FUNCTIONS
BREAKOUT
MAINTAINABILITY
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B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
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F - LT HEINS
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H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
MAN HOURS
1.0
.5
0
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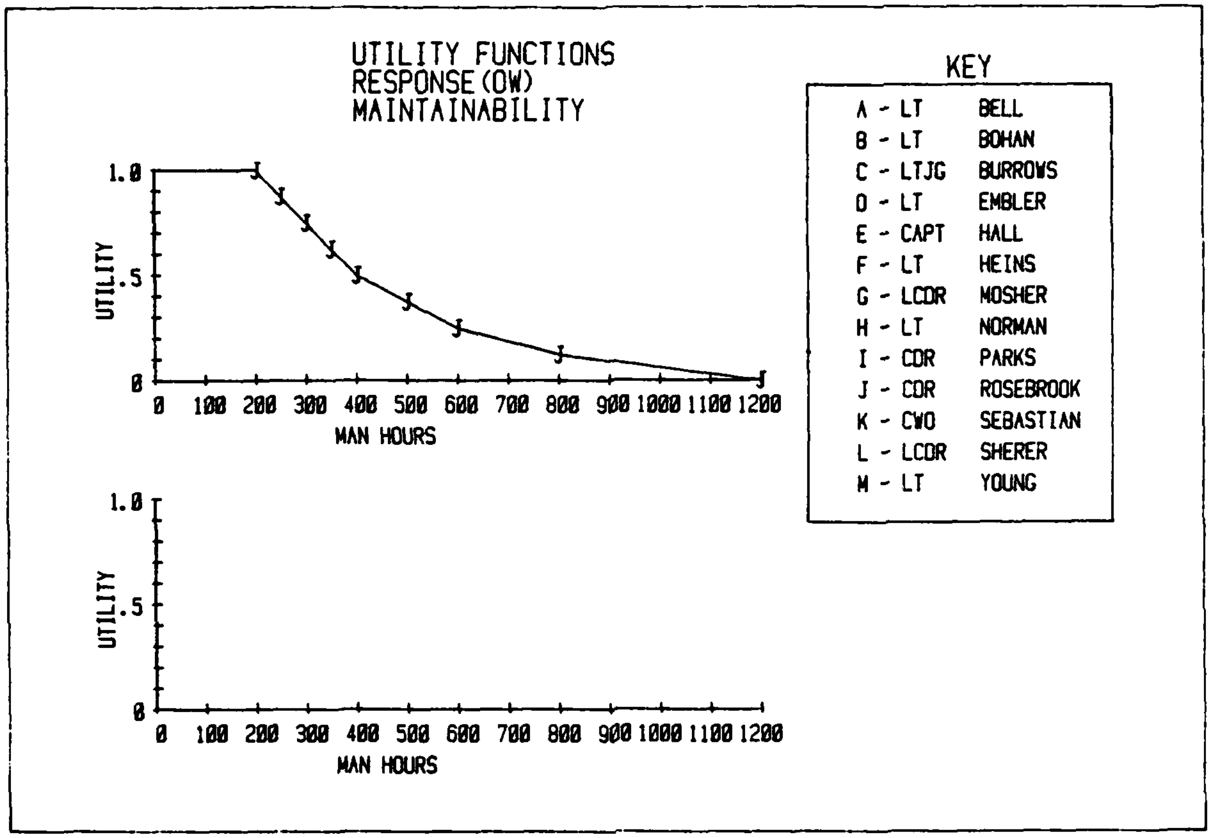
UTILITY FUNCTIONS
RESPONSE (OW)
MAINTAINABILITY
1.0
UTILITY .5
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MAN HOURS
1.0
UTILITY .5
0
0 100 200 300 400 500 600 700 800 900 1000 1100 1200
MAN HOURS
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
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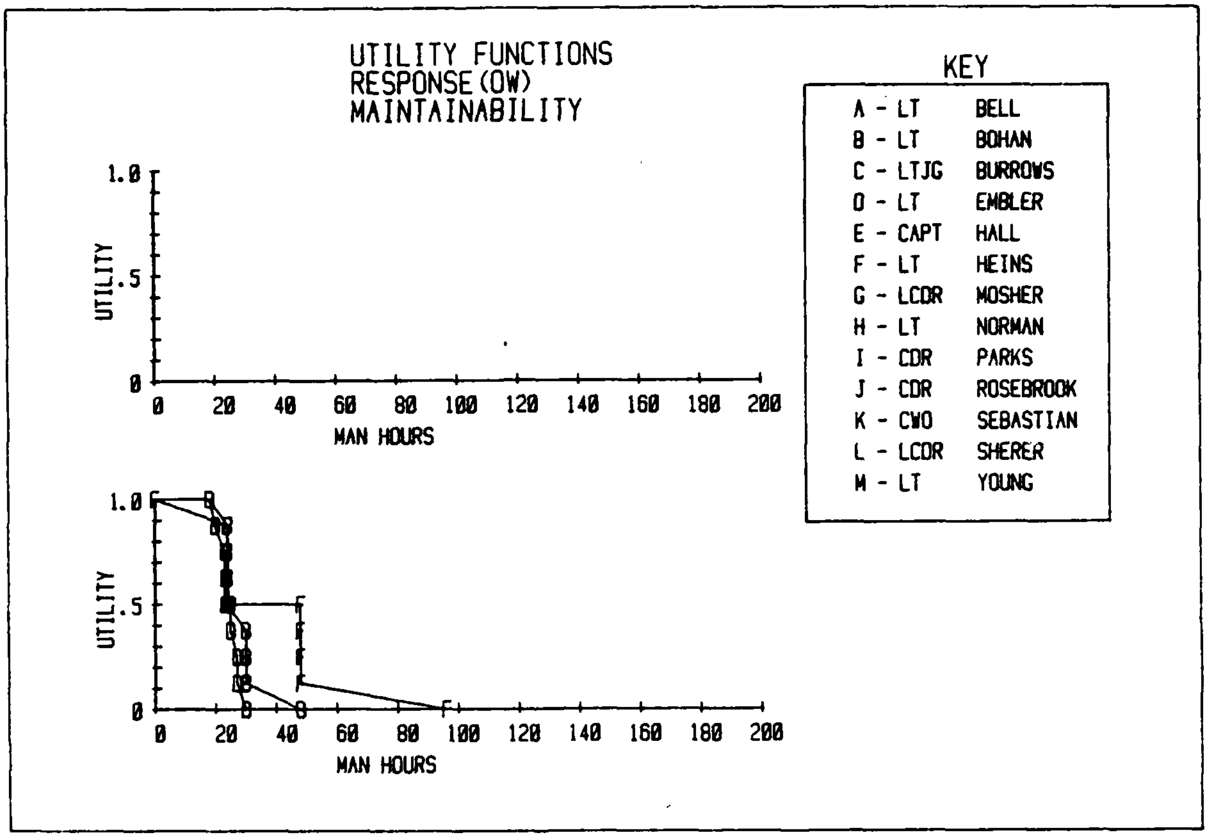
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG


UTILITY FUNCTIONS
RESPONSE (OW)
MAINTAINABILITY
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B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
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F - LT HEINS
G - LCDR MOSHER
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I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
MAN HOURS
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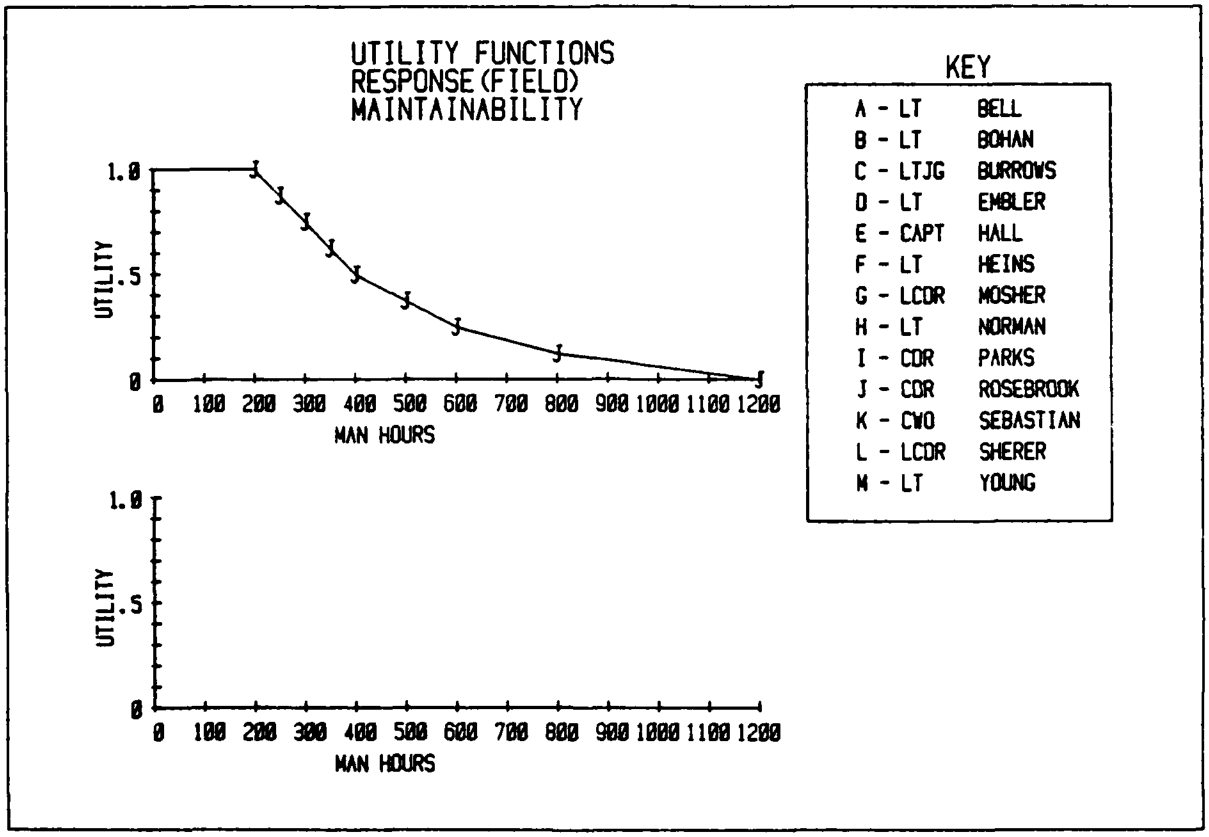
UTILITY FUNCTIONS
RESPONSE (FIELD)
MAINTAINABILITY
KEY
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B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
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G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
1.0
.5
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UTILITY
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MAN HOURS
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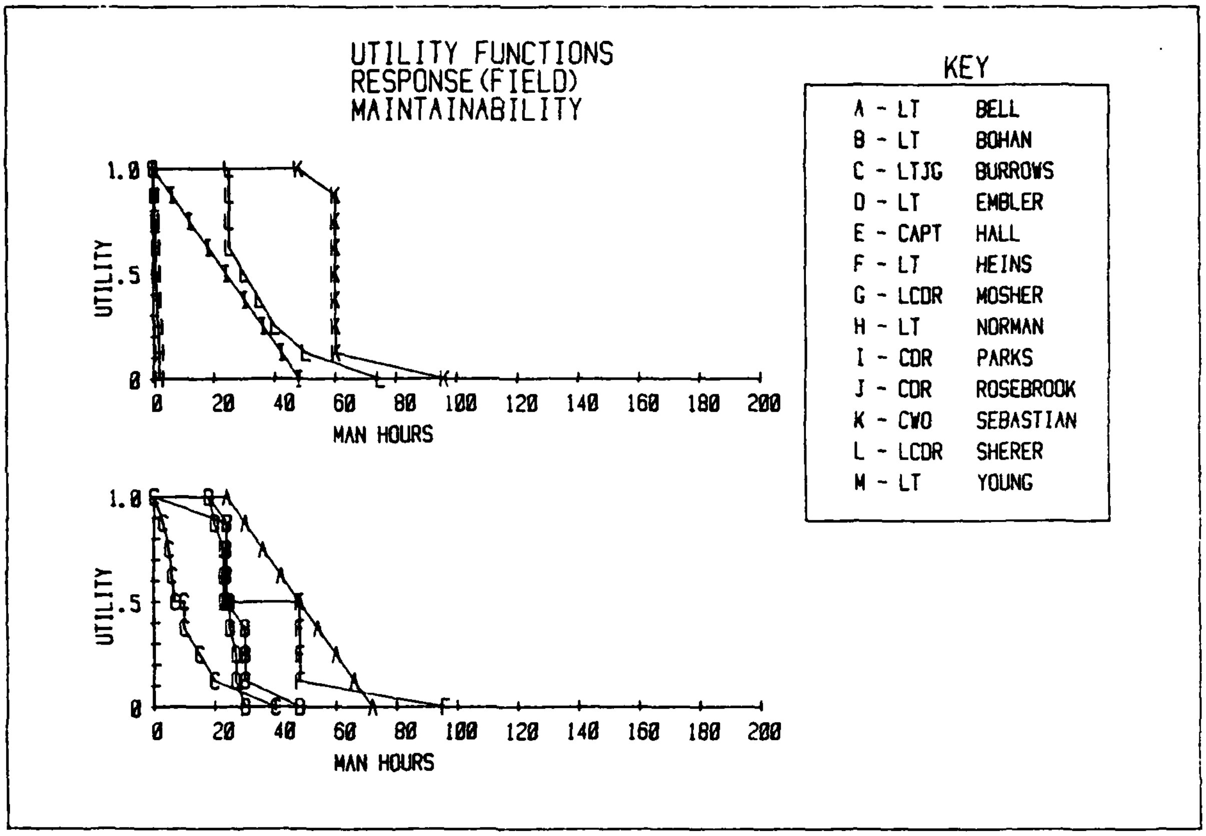
MAN HOURS



UTILITY FUNCTIONS
RESPONSE (FIELD)
MAINTAINABILITY
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B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
MAN HOURS
1.0
.5
0
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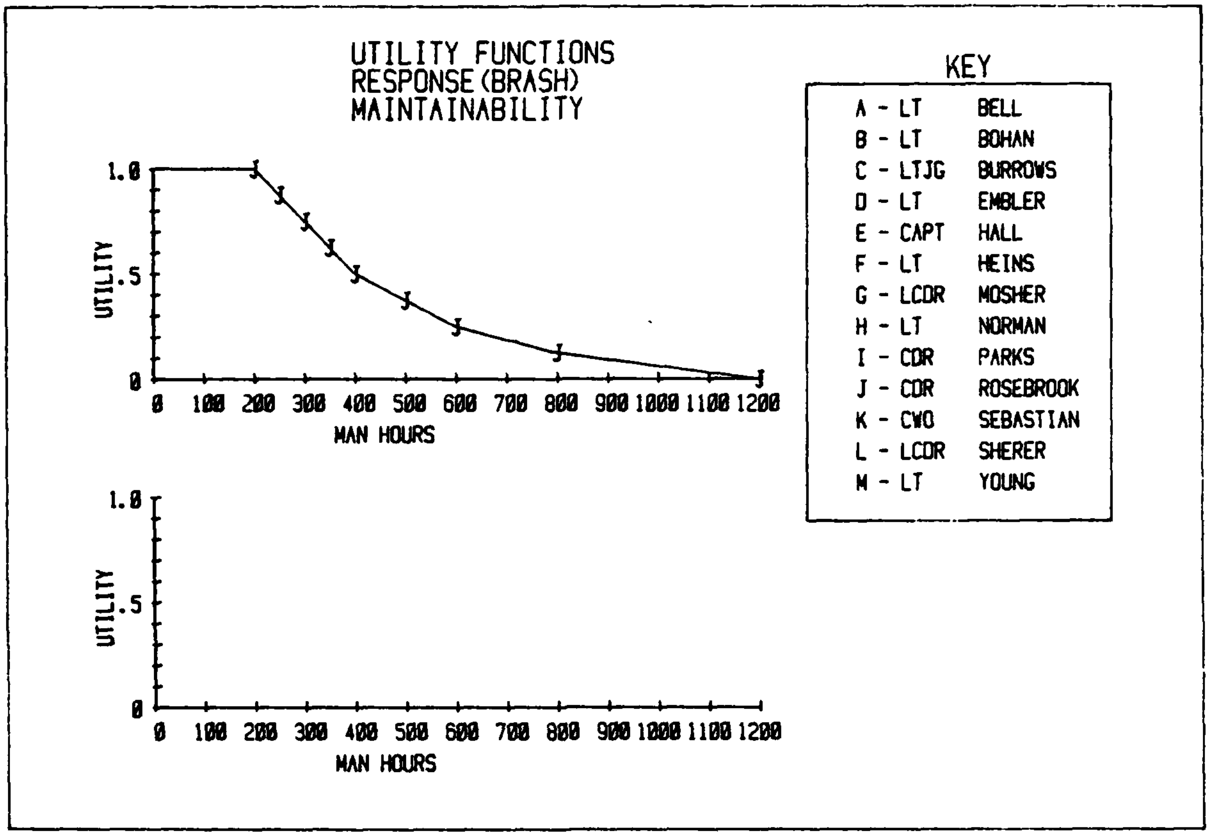
UTILITY FUNCTIONS
RESPONSE (BRASH)
MAINTAINABILITY
UTILITY
1.0
.5
0
0 100 200 300 400 500 600 700 800 900 1000 1100 1200
MAN HOURS
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
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I - CDR PARKS
J - CDR ROSEBROOK
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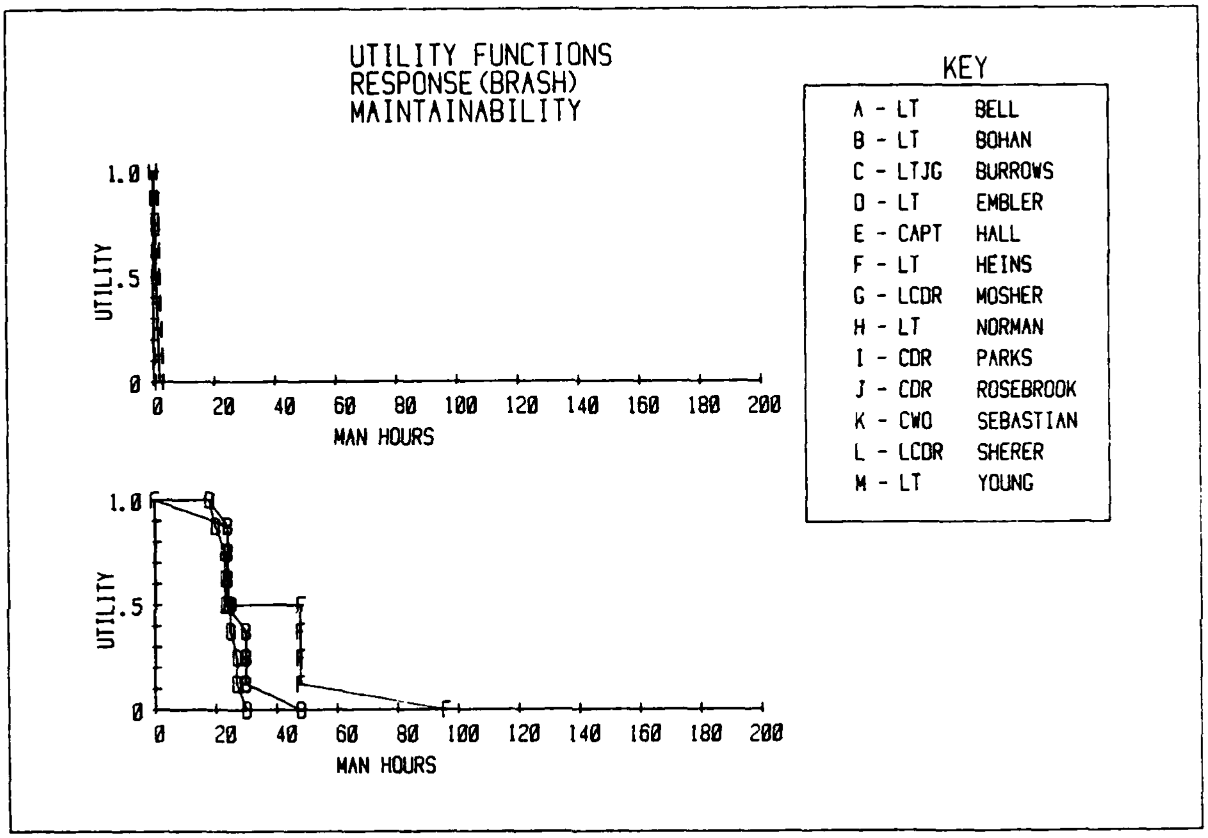
L - LCDR SHERER
M - LT YOUNG


UTILITY FUNCTIONS
RESPONSE (BRASH)
MAINTAINABILITY
KEY
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B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
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F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
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0
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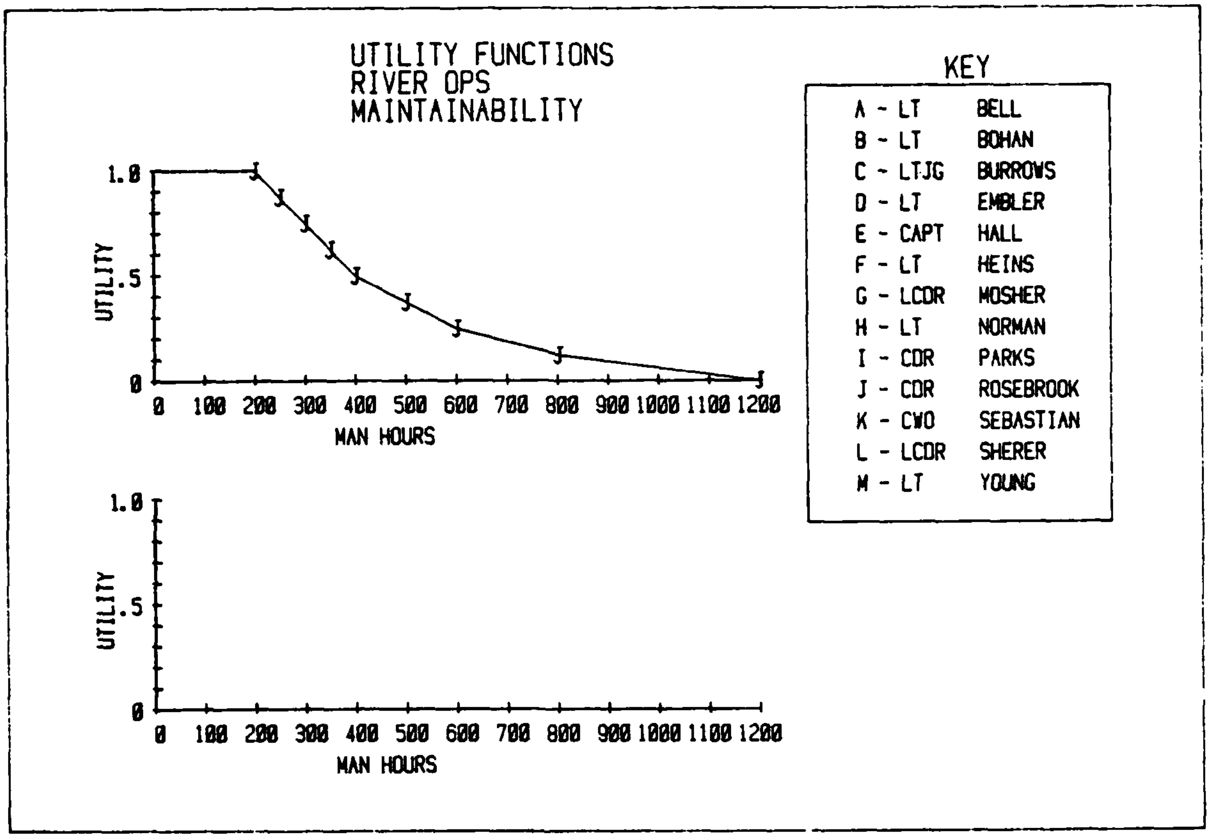
MAN HOURS
UTILITY
1.0
.5
0
0 20 40 60 80 100 120 140 160 180 200
MAN HOURS


UTILITY FUNCTIONS
RIVER OPS
MAINTAINABILITY
UTILITY
1.0
.5
0
0 100 200 300 400 500 600 700 800 900 1000 1100 1200
MAN HOURS
UTILITY
1.0
.5
0
0 100 200 300 400 500 600 700 800 900 1000 1100 1200
MAN HOURS
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
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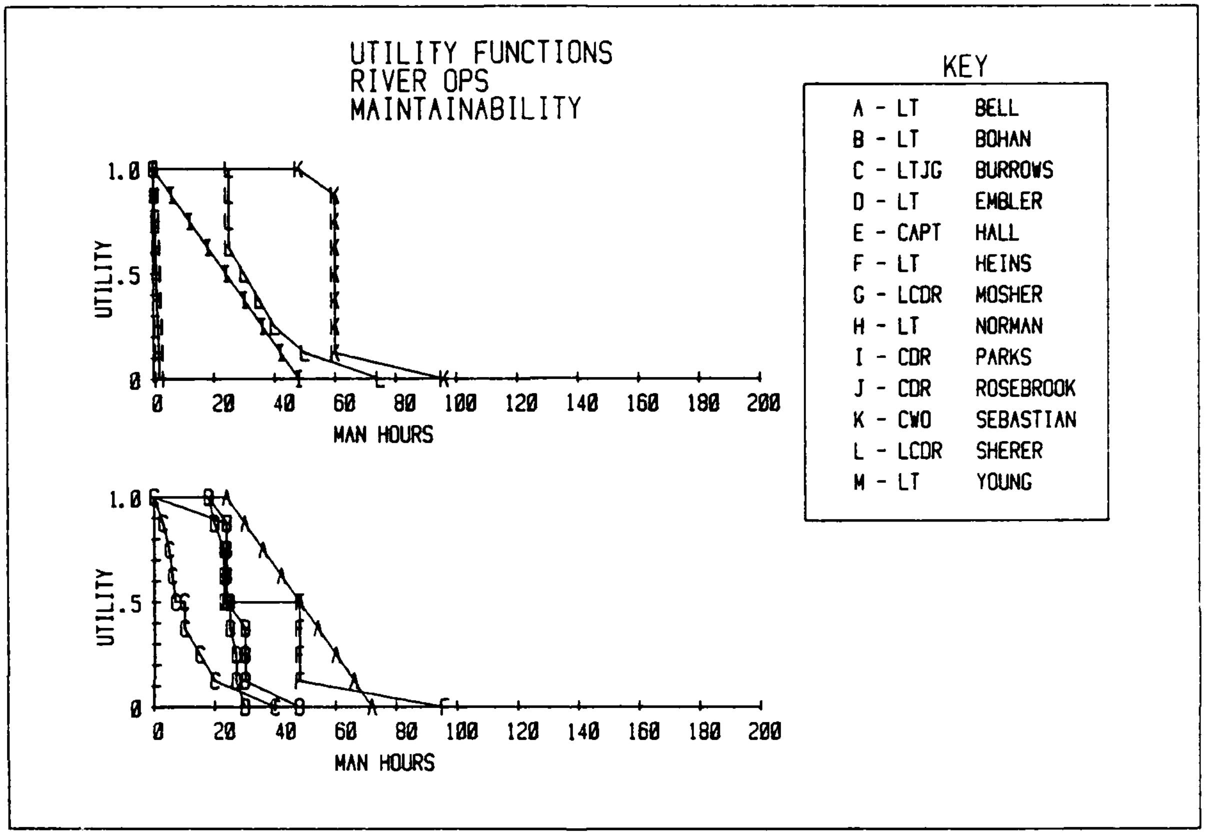
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG


UTILITY FUNCTIONS
RIVER OPS
MAINTAINABILITY
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
MAN HOURS
1.0
.5
0
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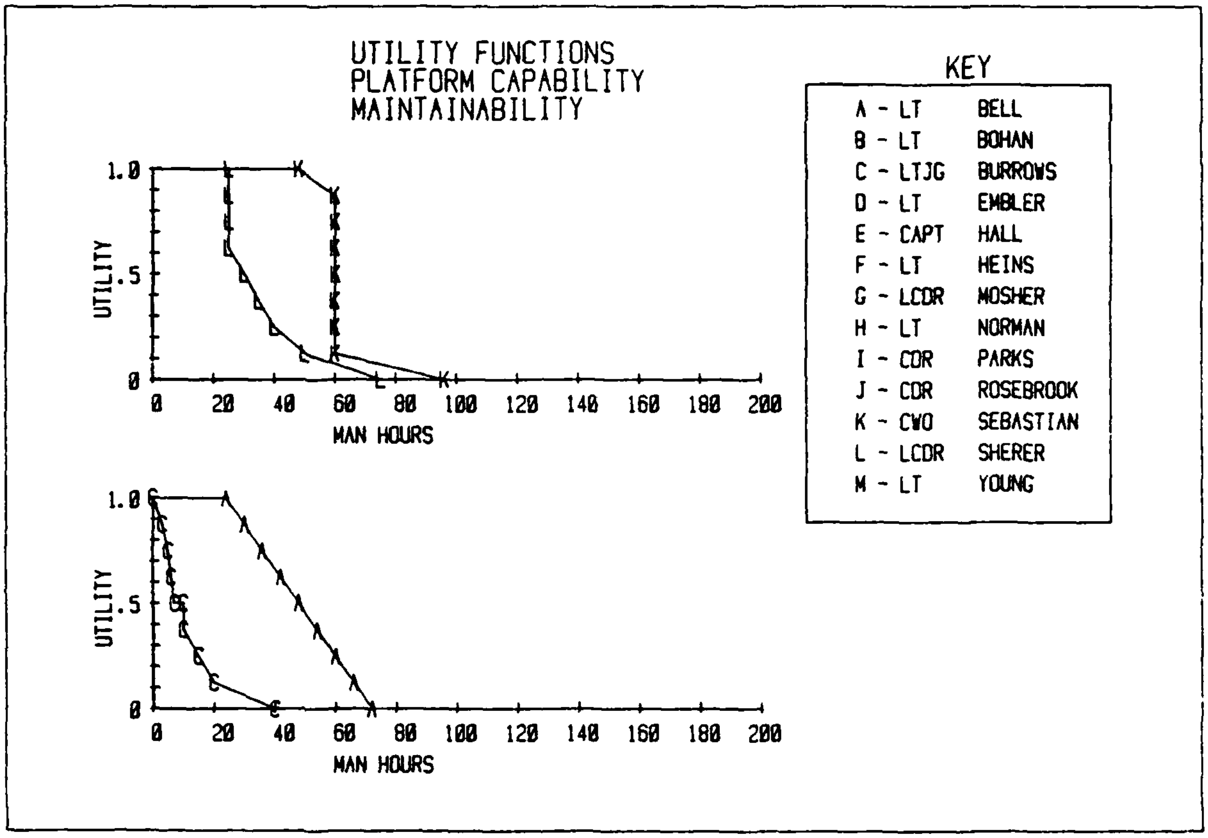

UTILITY FUNCTIONS
PLATFORM CAPABILITY
MAINTAINABILITY
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 20 40 60 80 100 120 140 160 180 200
MAN HOURS
UTILITY
1.0
.5
0
0 20 40 60 80 100 120 140 160 180 200
MAN HOURS

AD-A110 560 COAST GUARD RESEARCH AND DEVELOPMENT CENTER GROTON CT F/G 13/10
COMPARATIVE ANALYSIS OF POTENTIAL AUXILIARY ICEBREAKING DEVICES--ETC(U)
JUN 81 J A SMITH, M J GOODWIN, M S MCBRIDE

UNCLASSIFIED CGR/DC-14/81 USCG-D-33-81 NL

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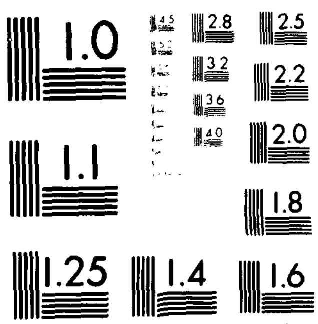
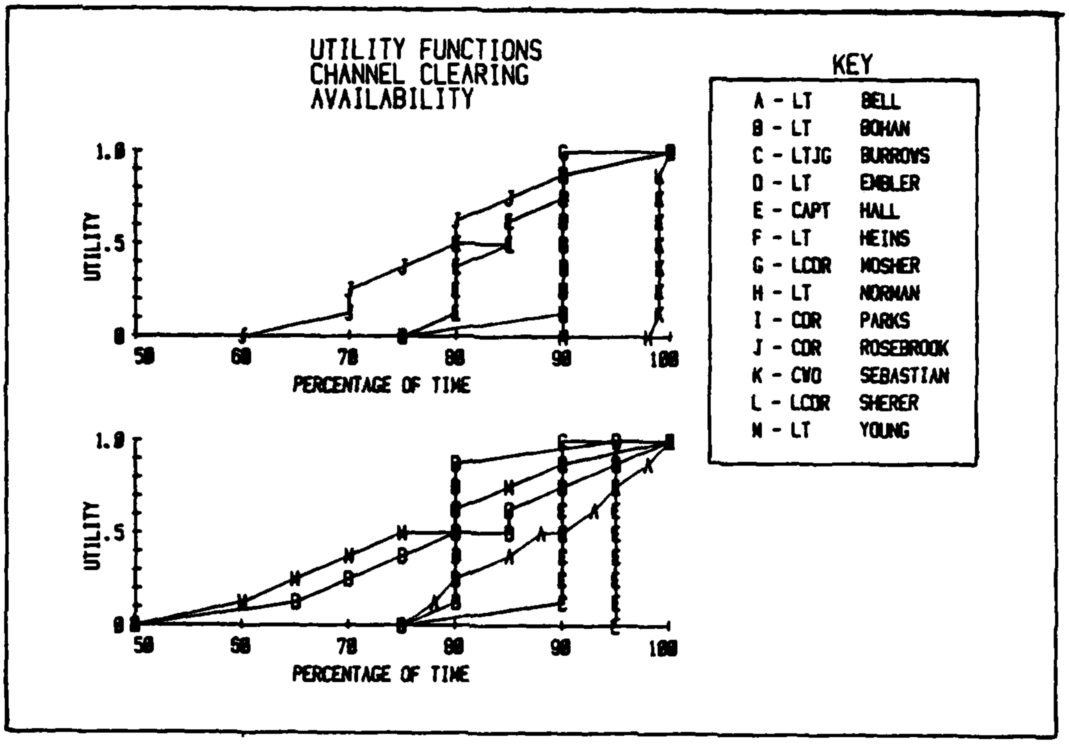


MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A


UTILITY FUNCTIONS
CHANNEL CLEARING
AVAILABILITY
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
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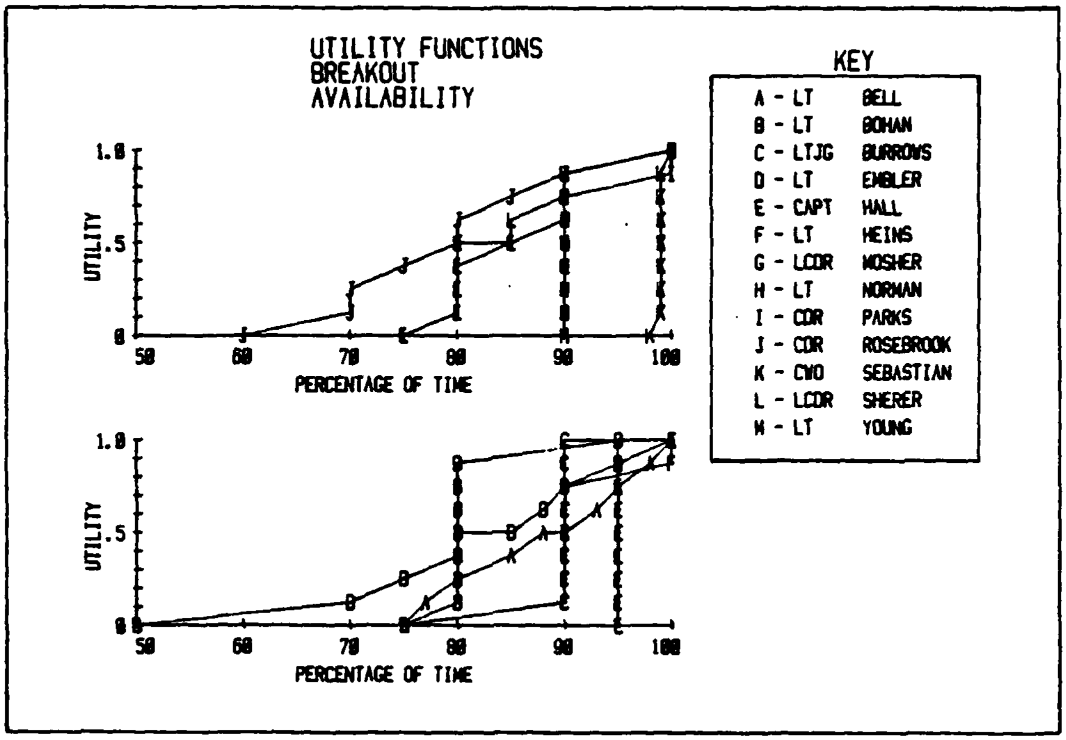
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
PERCENTAGE OF TIME


UTILITY FUNCTIONS
BREAKOUT
AVAILABILITY
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
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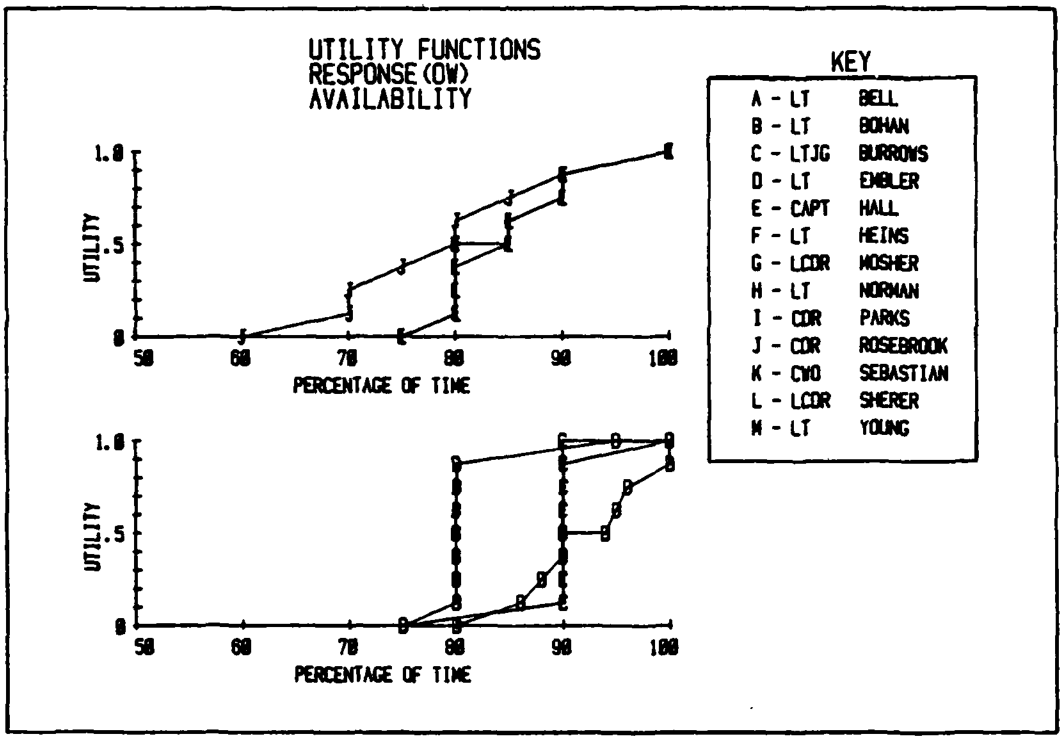
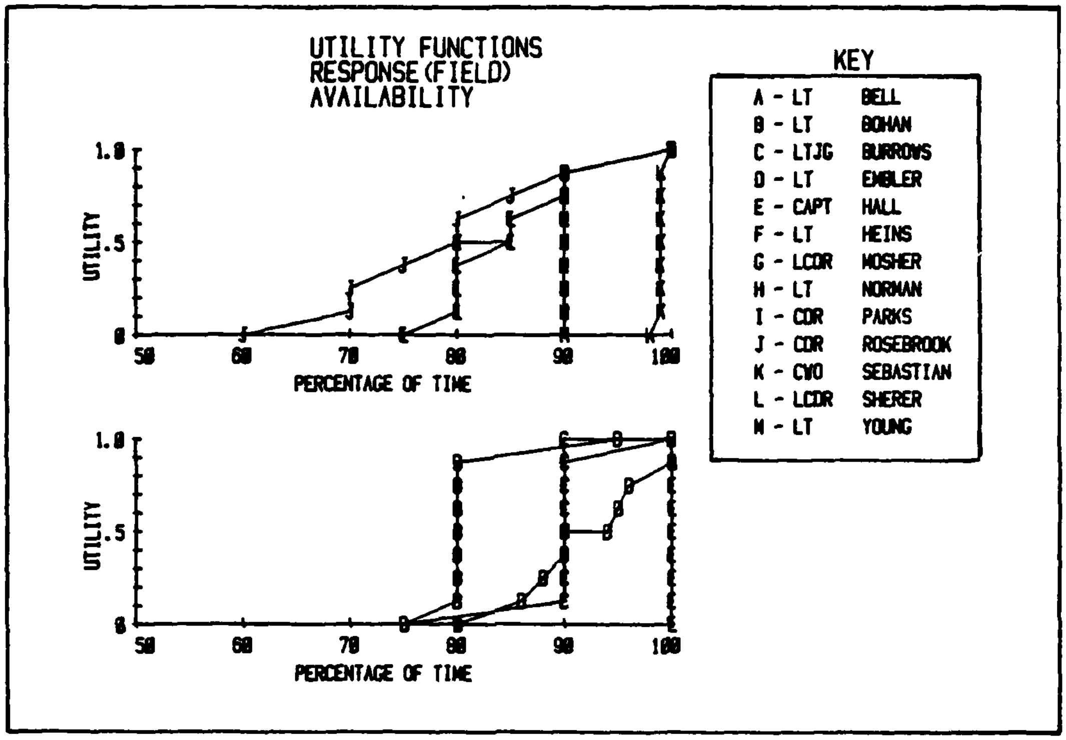
L - LCDR SHERER
M - LT YOUNG
UTILITY
PERCENTAGE OF TIME
UTILITY
PERCENTAGE OF TIME



UTILITY FUNCTIONS
RESPONSE (OW)
AVAILABILITY
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
50
60
70
80
90
100
PERCENTAGE OF TIME


UTILITY FUNCTIONS
RESPONSE (FIELD)
AVAILABILITY
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
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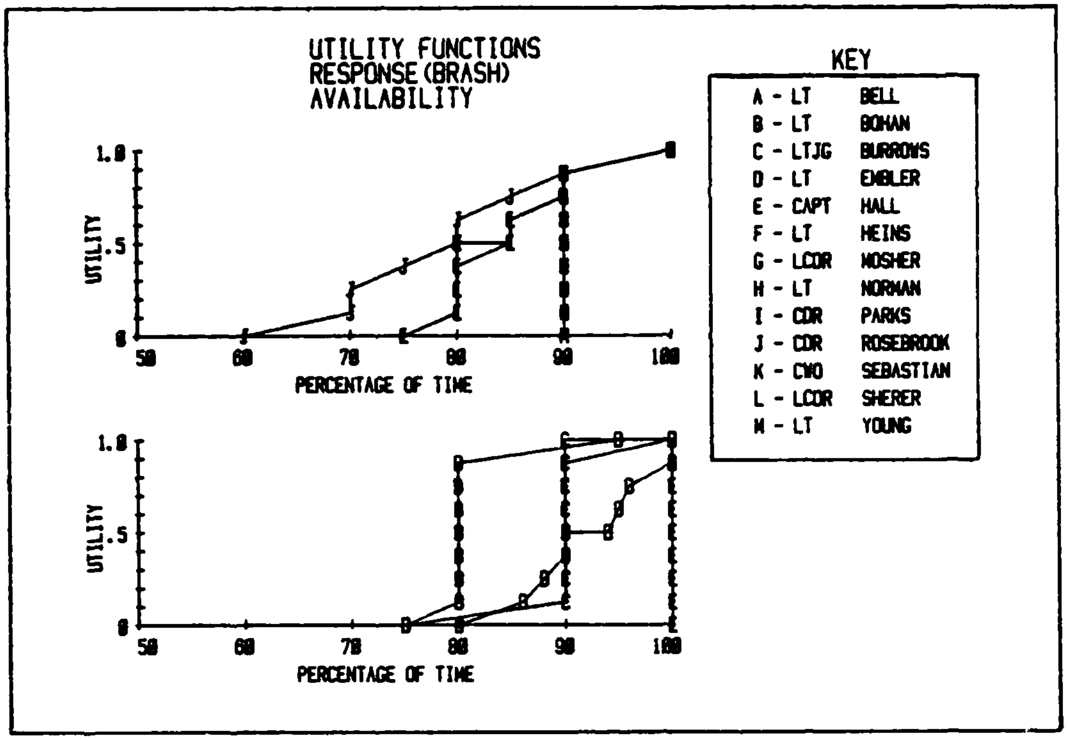
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
PERCENTAGE OF TIME
1.0
.5
0
50
60
70
80
90
100


UTILITY FUNCTIONS
RESPONSE (BRASH)
AVAILABILITY
KEY
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B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
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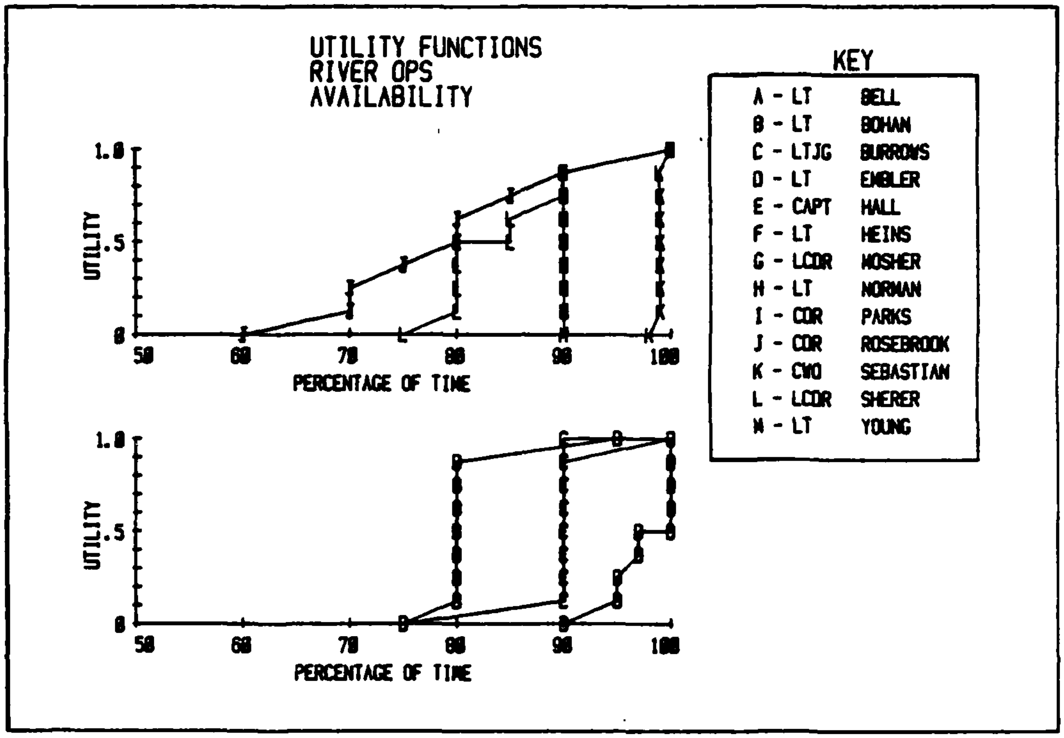
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
50
60
70
80
90
100
PERCENTAGE OF TIME
UTILITY
1.0
.5
0
50
60
70
80
90
100
PERCENTAGE OF TIME


UTILITY FUNCTIONS
RIVER OPS
AVAILABILITY
KEY
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B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
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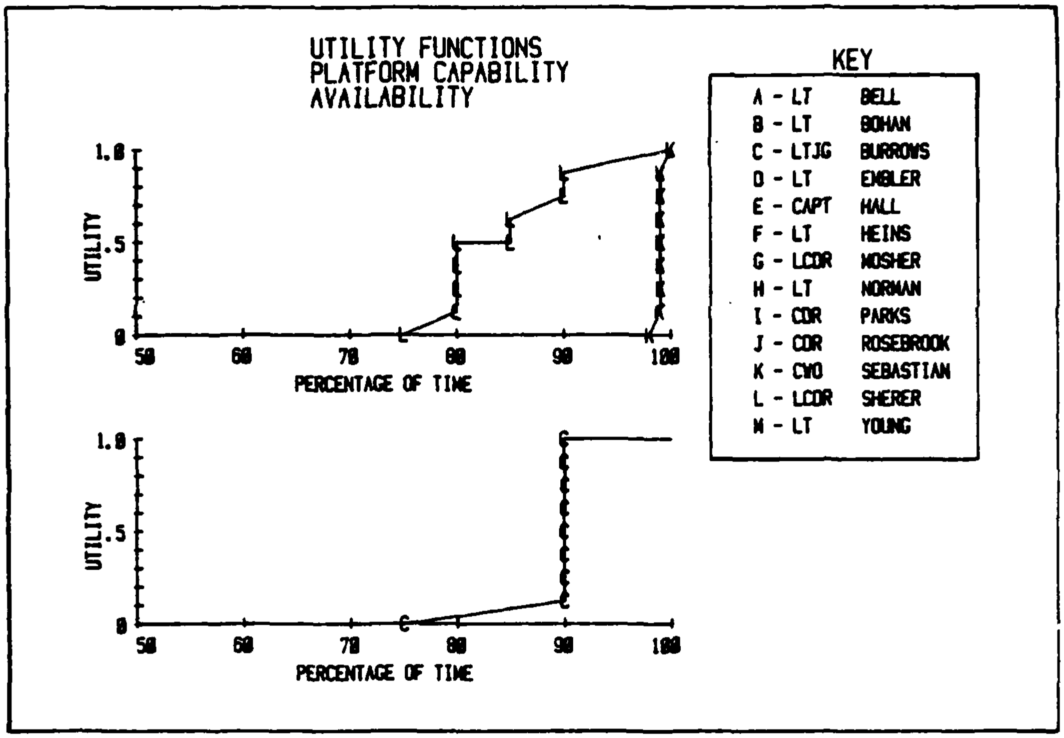
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
PERCENTAGE OF TIME



UTILITY FUNCTIONS
PLATFORM CAPABILITY
AVAILABILITY
KEY
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B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
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I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
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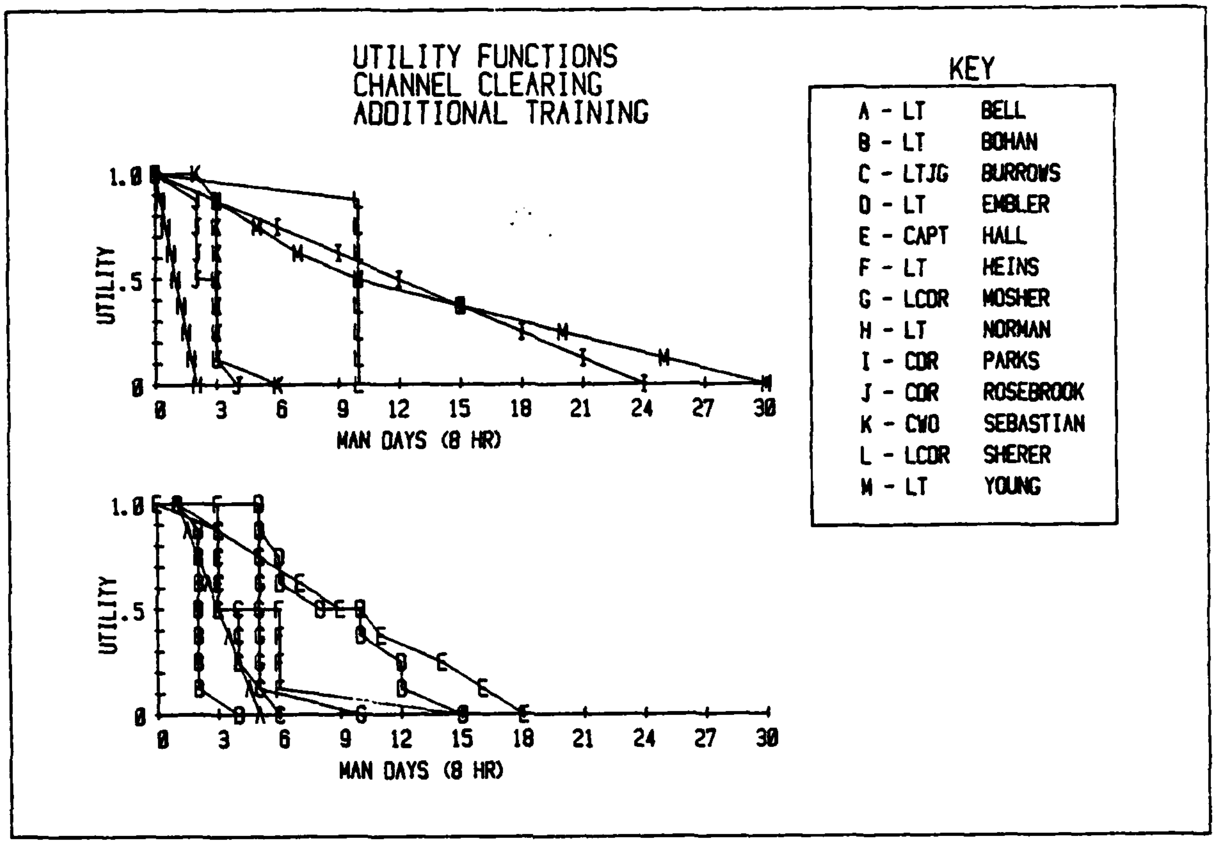
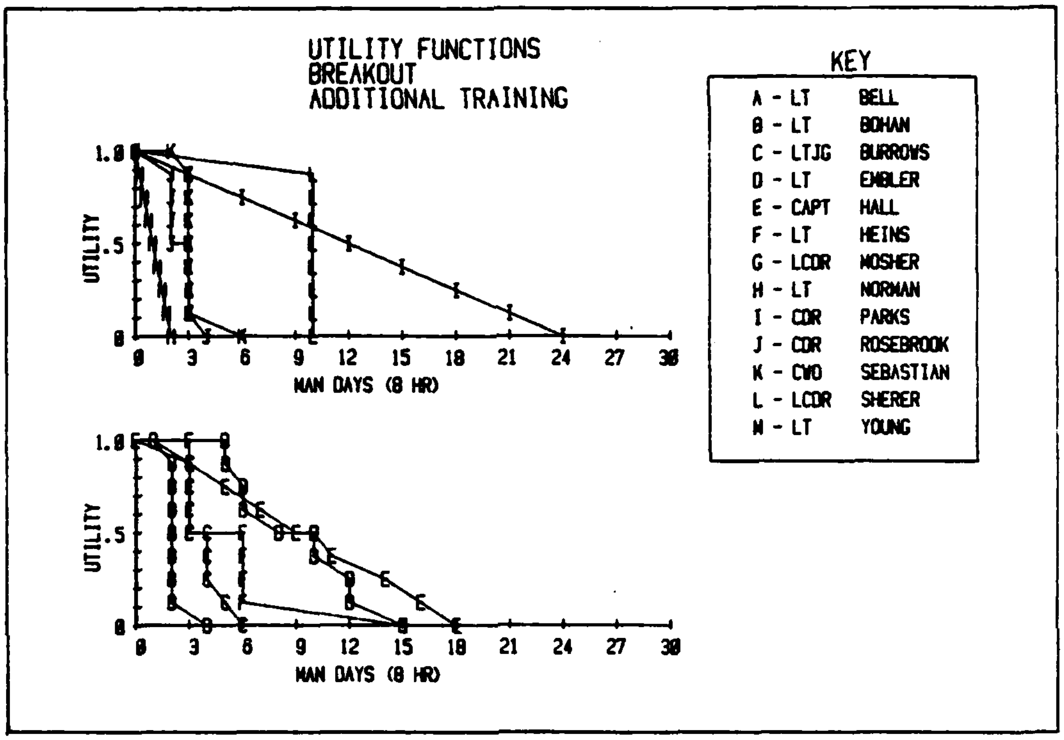
0
50
60
70
80
90
100
PERCENTAGE OF TIME



UTILITY FUNCTIONS
CHANNEL CLEARING
ADDITIONAL TRAINING
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 3 6 9 12 15 18 21 24 27 30
MAN DAYS (8 HR)



UTILITY FUNCTIONS
BREAKOUT
ADDITIONAL TRAINING
KEY
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B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
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F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
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0 3 6 9 12 15 18 21 24 27 30
MAN DAYS (8 HR)
UTILITY
1.0
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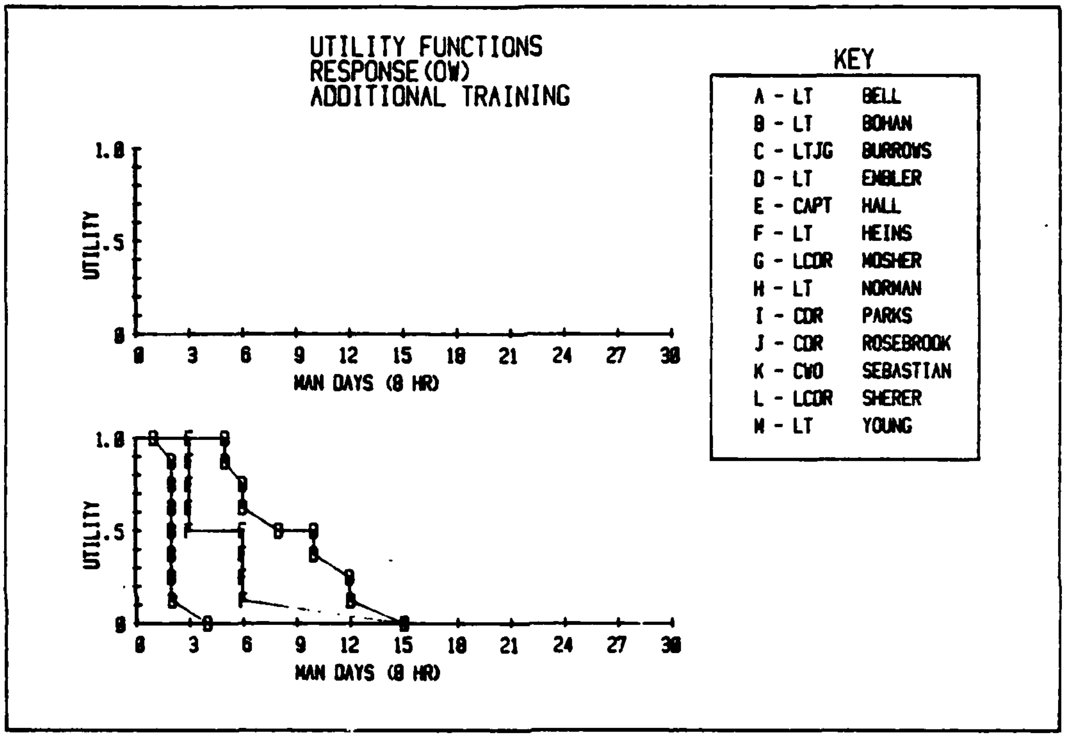
0 3 6 9 12 15 18 21 24 27 30
MAN DAYS (8 HR)



UTILITY FUNCTIONS
RESPONSE (OW)
ADDITIONAL TRAINING
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G - LCDR MOSHER
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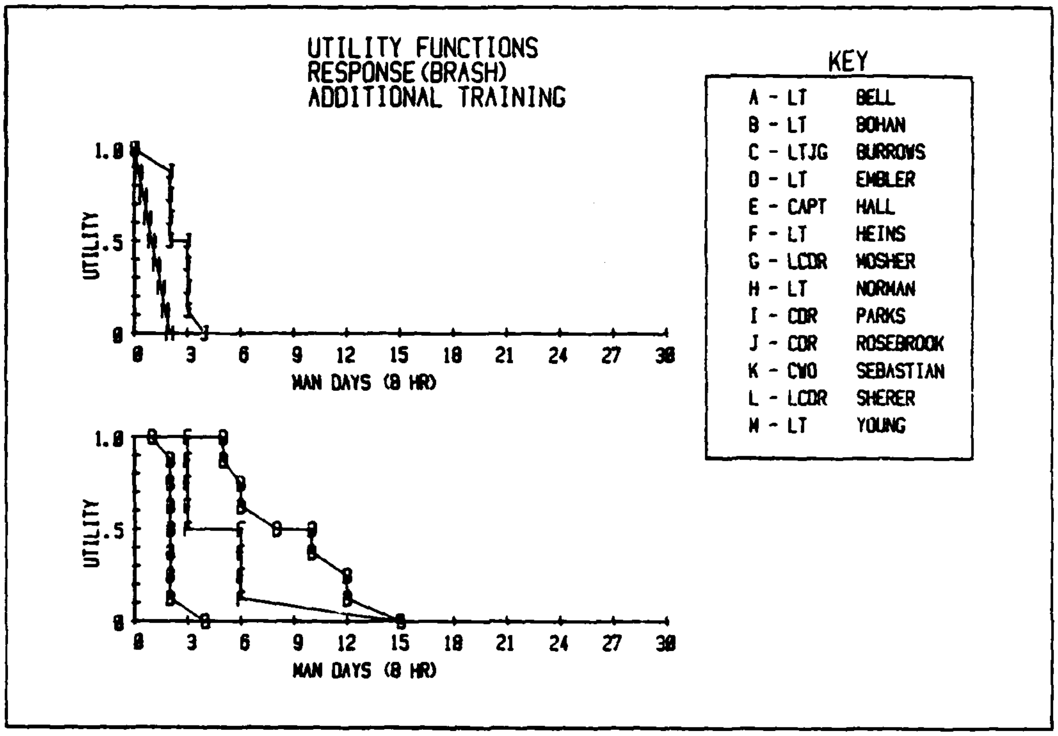
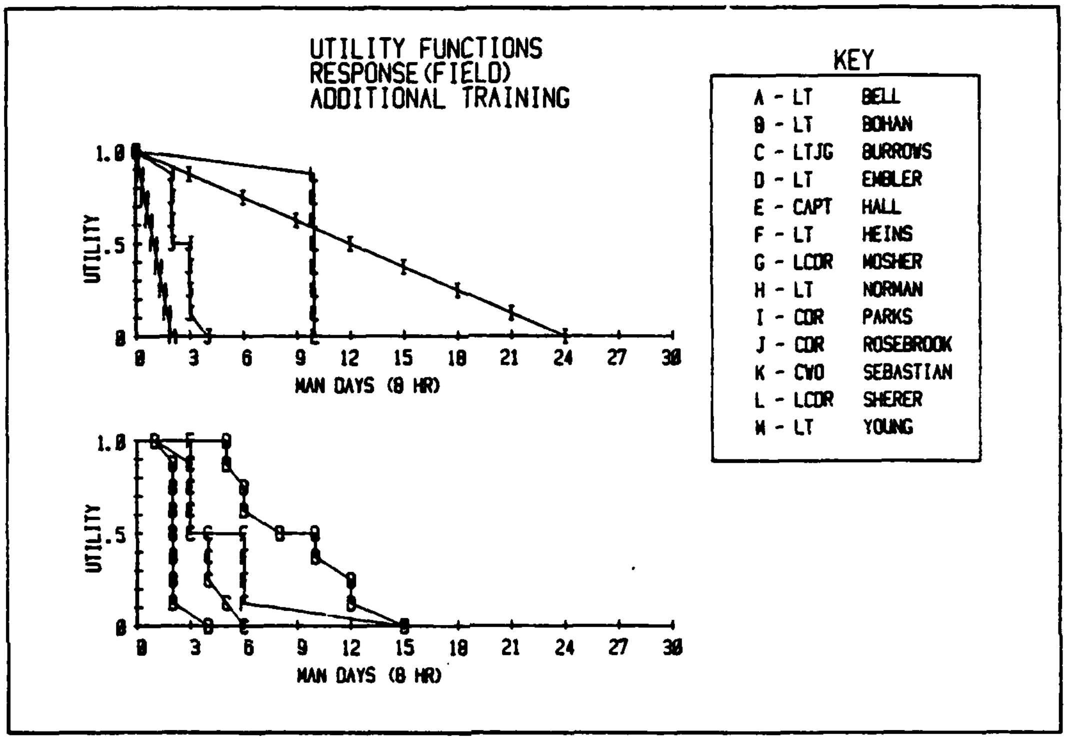
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 3 6 9 12 15 18 21 24 27 30
MAN DAYS (8 HR)
UTILITY
1.0
.5
0
0 3 6 9 12 15 18 21 24 27 30
MAN DAYS (8 HR)


UTILITY FUNCTIONS
RESPONSE (BRASH)
ADDITIONAL TRAINING
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 3 6 9 12 15 18 21 24 27 30
MAN DAYS (8 HR)
UTILITY
1.0
.5
0
0 3 6 9 12 15 18 21 24 27 30
MAN DAYS (8 HR)


UTILITY FUNCTIONS
RESPONSE (FIELD)
ADDITIONAL TRAINING
KEY
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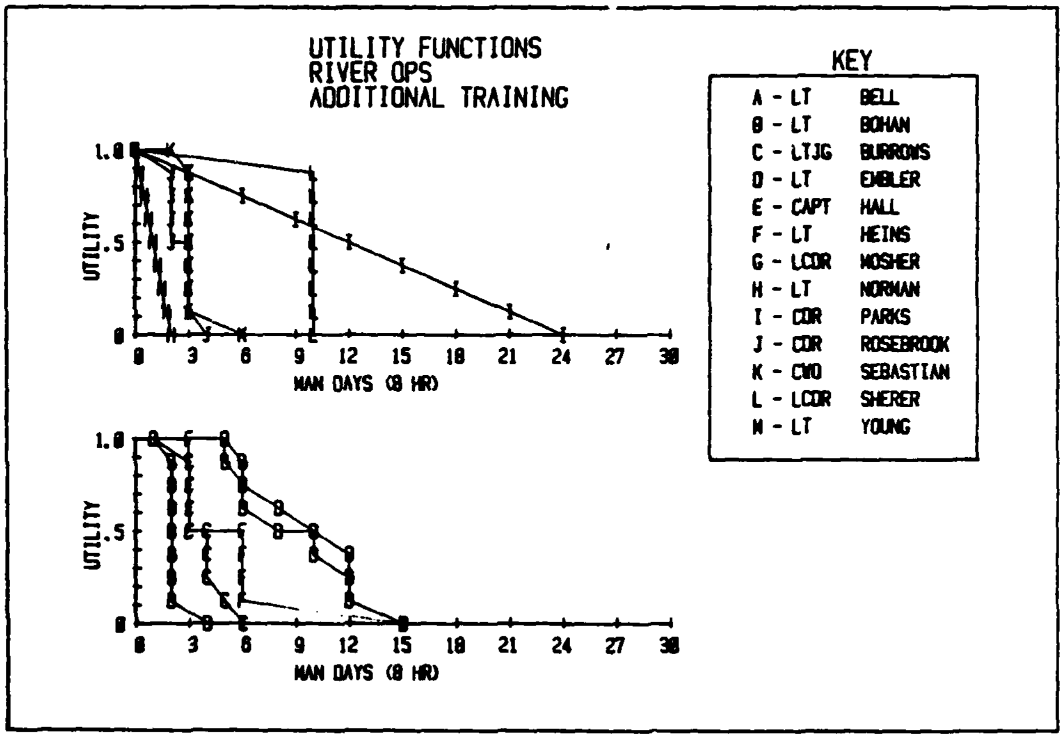
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
MAN DAYS (8 HR)
1.0
.5
0
0 3 6 9 12 15 18 21 24 27 30


UTILITY FUNCTIONS
RIVER OPS
ADDITIONAL TRAINING
KEY
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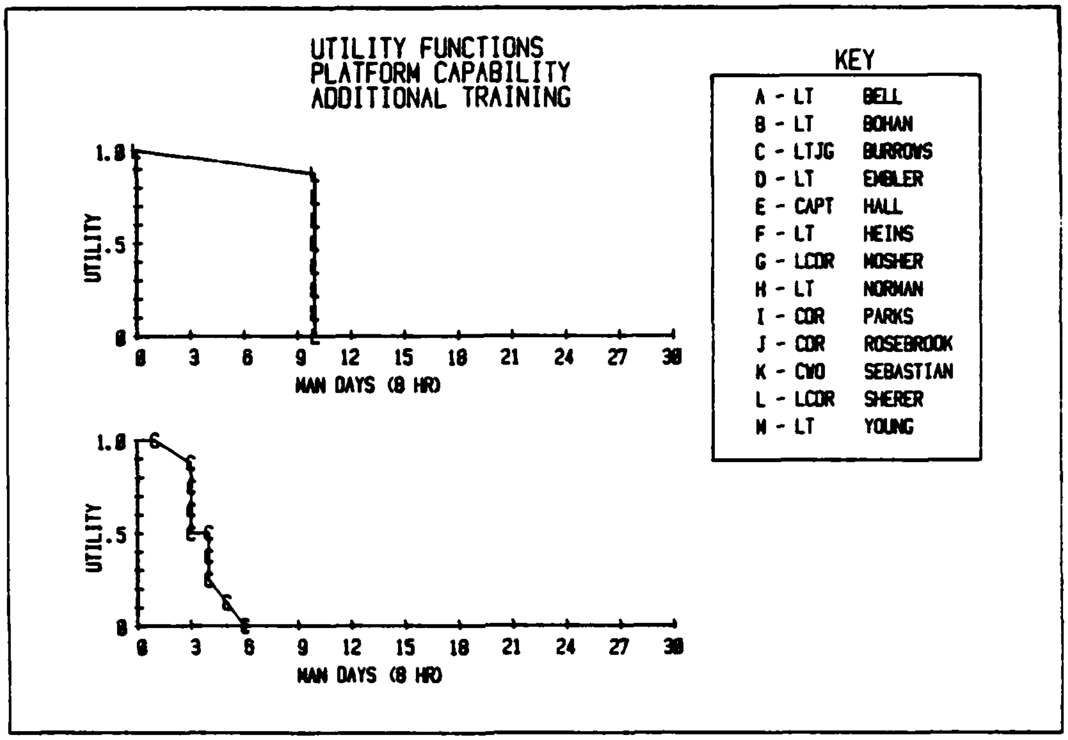
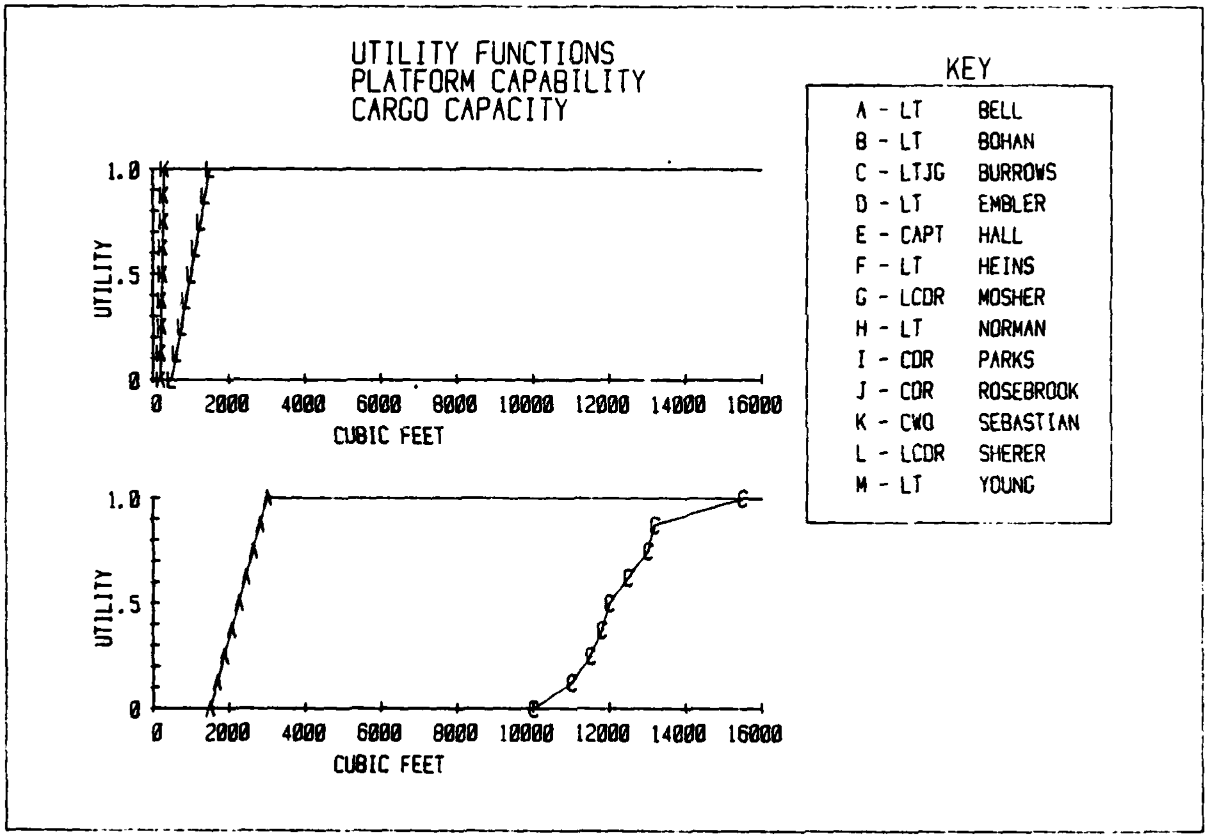
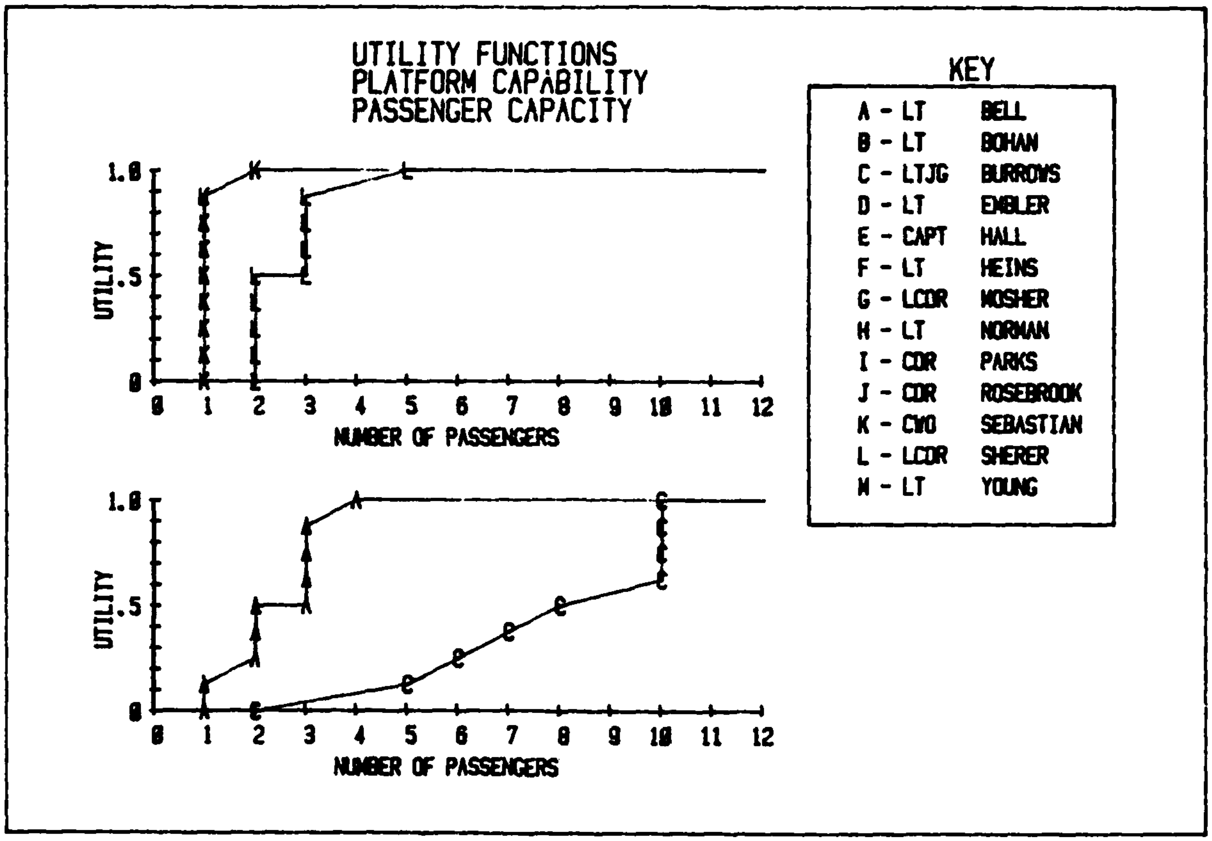
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
MAN DAYS (8 HR)
UTILITY
MAN DAYS (8 HR)


UTILITY FUNCTIONS
PLATFORM CAPABILITY
ADDITIONAL TRAINING
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 3 6 9 12 15 18 21 24 27 30
MAN DAYS (8 HR)
UTILITY
1.0
.5
0
0 3 6 9 12 15 18 21 24 27 30
MAN DAYS (8 HR)


UTILITY FUNCTIONS
PLATFORM CAPABILITY
CARGO CAPACITY
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 2000 4000 6000 8000 10000 12000 14000 16000
CUBIC FEET
UTILITY
1.0
.5
0
0 2000 4000 6000 8000 10000 12000 14000 16000
CUBIC FEET



UTILITY FUNCTIONS
PLATFORM CAPABILITY
PASSENGER CAPACITY
KEY
A - LT BELL
B - LT BOHAN
C - LTJG BURROWS
D - LT EMBLER
E - CAPT HALL
F - LT HEINS
G - LCDR MOSHER
H - LT NORMAN
I - CDR PARKS
J - CDR ROSEBROOK
K - CWO SEBASTIAN
L - LCDR SHERER
M - LT YOUNG
UTILITY
1.0
.5
0
0 1 2 3 4 5 6 7 8 9 10 11 12
NUMBER OF PASSENGERS
UTILITY
1.0
.5
0
0 1 2 3 4 5 6 7 8 9 10 11 12
NUMBER OF PASSENGERS

APPENDIX G

APPENDIX G

Sensitivity Analysis

Parametric models are concerned with sensitivity analysis, or the partial derivatives of a function. Given a function of the form

$$Ax + By + Cz + Dm + En = R \tag{G-1}$$

The question is "what is the effect on R of changes in A when B, C, D, and E are constant and what is the effect on R of changes in B when A, C, D, and E are constant, and so on?"

This approach has been applied to the final matrices given in Volume 2, after an optimum alternative has been determined. This will indicate to the analyst the sensitivity of the outcome to changes in the level of each attribute. For simplicity, the partial derivative of a parameter is expressed as a percentage of the nominal value. In the general form

$$Ax + By + Cz + Dm + En = R \tag{G-2}$$

each coefficient is varied plus or minus P% in increments of S% and the effect on R is tabulated. If for example x=2, y=3, z=4, m=5, n=6, A=8, B=5, C=3, D=4, E=2, then in the nominal case

$$\begin{aligned} R &= 8(2) + 5(3) + 3(4) + 4(5) + 2(6) \\ &= 16 + 15 + 12 + 20 + 12 \\ &= 75 \end{aligned} \tag{G-3}$$

If A is changed by plus 25%

$$R = 20 + 15 + 12 + 20 + 12 = 79 \text{ or the change in R is } 5.33\% \tag{G-4}$$

For the optimum alternative, the weighted average utility is

$$A = \sum u_j W_j \tag{G-5}$$

where u_j are the optimum utilities.

Each optimum parameter utility is varied, in turn, plus or minus P percent in increments of S percent to yield (2 P/S + 1)M values.) These values are then tabulated. The model output is a table of weighted averages where nominal value (no deviation) is the same for all parameters. For convenience, the deviation is expressed as a factor ranging from 1-P/100 to 1+P/100. The nominal values then have a deviation factor of 1.

Algorithm for incrementing from -10% to +10%.

B = Initial Value = 0% Value = A(11)

A(1) = 0.89B + 0.01B = 0.90B		= -10%
A(2) = 0.89B + 0.02B = 0.91B		= -9%
.		
.		
.		
A(11) = 0.89B + 0.11B = 1.00B		= $\underline{+}$ %
A(12) = 0.89B + 0.12B = 1.01B		= $\overline{+}$1%
.		
.		
.		
A(21) = 0.89B + 0.21B		= +10%
A(I) = 0.89B + (I/100)B		= (I-11)%

NOTE: The first value is 90% of B, but since 1% is being added, the constant is (0.90-0.01)B = 0.89B

In the general case, when the percentage variation is P and the increment is S, the number of values for each parameter is 2PS+1, i.e., the number of values in a column. The first value is (100-P) percent of B where B is the nominal value. Since the increments being added is S percent, the constant is (100-P-S)B, then

$$A(I) = \frac{100-P-S}{100} B + \frac{S}{100} B \tag{G-6}$$

where I, the index, has the range 2P/S+1. For example, when P=20% and S=5%, the range of I is from 1 to 9.

Then in this example

$$A(1) = \frac{100-20-5}{100} B + \frac{1x5}{100} B \tag{G-7}$$

$$\begin{aligned} &= 0.75B + 0.05B = 0.80B = -20\% \\ A(5) &= 0.75B + 0.25B = 1.00B = \underline{+}0\% \\ A(9) &= 0.75 + 0.45B = 1.20B = +\overline{2}0\% \end{aligned}$$

APPENDIX H

APPENDIX H

GLOSSARY OF TERMS

Administration - One who administers something; an executive. Relating to the putting into effect of plans, projects, work programs, etc.

Alternative - A possible course of action. In the case of this problem, an auxiliary device.

Attribute - A measure of performance of the auxiliary device/icebreaker system.

Auxiliary - Giving or furnishing aid. Subsidiary; accessory. Supplementary; reserve.

Axiom - A self-evident proposition accepted as true without proof.

Bilge - The part of the underwater body of a ship between the flat of the bottom and the vertical topsides; lowest point of a ship's inner hull. Rounded part of a ship's bottom.

Bilge Keel - A longitudinal projection like a fin secured on either side to check rolling.

Cardinal Number - Any number that expresses the number of objects or units under consideration, as 1, 2, 3, etc.; distinguished from ordinal number.

Criterion - A standard or rule by which a judgment can be made; a model, feet, or measure.

Decidability - Concerned with the "proof" of a proposition, or its negation, based on a set of axioms and two-valued logic.

Eigenvalue - A value of λ for which the matrix equation

$$Ax = \lambda x$$

has a solution where $x \neq 0$ where A is a square matrix and "λ" is a number.

Eigenvector - The solutions x of the equation

$$Ax = \lambda x$$

where $x \neq 0$. A separate eigenvector exists for each eigenvalue.

Engineering - The art and science of designing, constructing, and operating roads, bridges, buildings, etc. Clever planning or maneuvering.

Function - (a) The specific natural, or proper action or activity of anything. Any fact, quality, or thing depending upon or varying with another. (b) Math. A quantity whose value is dependent on the value of some other quantity.

Hierarchical Structure - The arrangement of individual elements according to a weighted order of importance.

Keel - A longitudinal timber of plate extending along the center of the bottom of a ship and often projecting from the bottom.

Lottery - A hypothetical situation in which two values of an attribute are given equal probability of occurrence.

Mathematics - The study of quantity, form, arrangement, and magnitude; especially the methods and processes for disclosing the properties and relations of quantities and magnitudes.

Mission Function - A subset of the overall mission of icebreaking; specific tasks performed while underway in ice.

Model - An object, usually in miniature and often built to scale, that represents something to be made or something already existing. A pattern, example, or standard that is or may be used for imitation in comparison.

Objective Function - In operations research; a function, usually of cost or profit which is to be maximized or minimized subject to constraints and requirements peculiar to the specific problem at hand.

Operator - One who operates a machine or mechanism.

Ordinal Number - A number that shows the order of a unit in a given series, as first, second, third, etc.; distinguished from cardinal number.

Probability Density Function - A curve over the range of an attribute which gives the probability that a value will be the maximum provided by a particular auxiliary device.

Scalar - Definable by a number on a line or scale: said of a quantity having magnitude only, as a volume or mass: distinguished from vector.

Threshold Value - The value of an attribute which separates the acceptable range from the undesirable range.

Utility - An arbitrary measure of value or contribution to success on a scale of 0 to 1.

Utility Function - A measure of utility over the range of an attribute.

Vector - A physical quantity that has magnitude and direction in space, as velocity and acceleration.

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